Ontario

Ontario Geological Survey
Open File Report 6172

Summary of Field Work and Other Activities 2005

2005

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6172

Summary of Field Work and Other Activities 2005

Edited by

C.L. Baker, E.J. Debicki, R.I. Kelly, J.A. Ayer, R.M. Easton and Z.B. Madon

2005

Parts of this publication may be quoted if credit is given. It is recommended that reference to this publication be made in the following form:

Hamilton, S.M., Hattori, K.H. and Clark, I.D. 2005. Investigation into the source of forest-ring-related natural gas in northern Ontario; *in* Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, p.19-1 to 19-4.

© Queen's Printer for Ontario, 2005

© Queen's Printer for Ontario, 2005.

Open File Reports of the Ontario Geological Survey are available for viewing at the Mines Library in Sudbury, at the Mines and Minerals Information Centre in Toronto, and at the regional Mines and Minerals office whose district includes the area covered by the report (see below).

Copies can be purchased at Publication Sales and the office whose district includes the area covered by the report. Although a particular report may not be in stock at locations other than the Publication Sales office in Sudbury, they can generally be obtained within 3 working days. All telephone, fax, mail and e-mail orders should be directed to the Publication Sales office in Sudbury. Use of VISA or MasterCard ensures the fastest possible service. Cheques or money orders should be made payable to the *Minister of Finance*.

Mines and Minerals Information Centre (MMIC) Tel: (416) 314-3800
Macdonald Block, Room M2-17
900 Bay St.
Toronto, Ontario M7A 1C3

Mines Library Tel: (705) 670-5615
933 Ramsey Lake Road, Level A3
Sudbury, Ontario P3E 6B5

Publication Sales Tel: (705) 670-5691(local)
933 Ramsey Lake Rd., Level A3 1-888-415-9845(toll-free)
Sudbury, Ontario P3E 6B5 Fax: (705) 670-5770
E-mail: pubsales@ndm.gov.on.ca

Regional Mines and Minerals Offices:

Kenora - Suite 104, 810 Robertson St., Kenora P9N 4J2

Kirkland Lake - 10 Government Rd. E., Kirkland Lake P2N 1A8

Red Lake - Box 324, Ontario Government Building, Red Lake P0V 2M0

Sault Ste. Marie - 70 Foster Dr., Ste. 200, Sault Ste. Marie P6A 6V8

Southern Ontario - P.O. Bag Service 43, 126 Old Troy Rd., Tweed K0K 3J0

Sudbury - Level B3, 933 Ramsey Lake Rd., Sudbury P3E 6B5

Thunder Bay - Suite B002, 435 James St. S., Thunder Bay P7E 6S7

Timmins - Ontario Government Complex, P.O. Bag 3060, Hwy. 101 East, South Porcupine P0N 1H0

Toronto - MMIC, Macdonald Block, Room M2-17, 900 Bay St., Toronto M7A 1C3

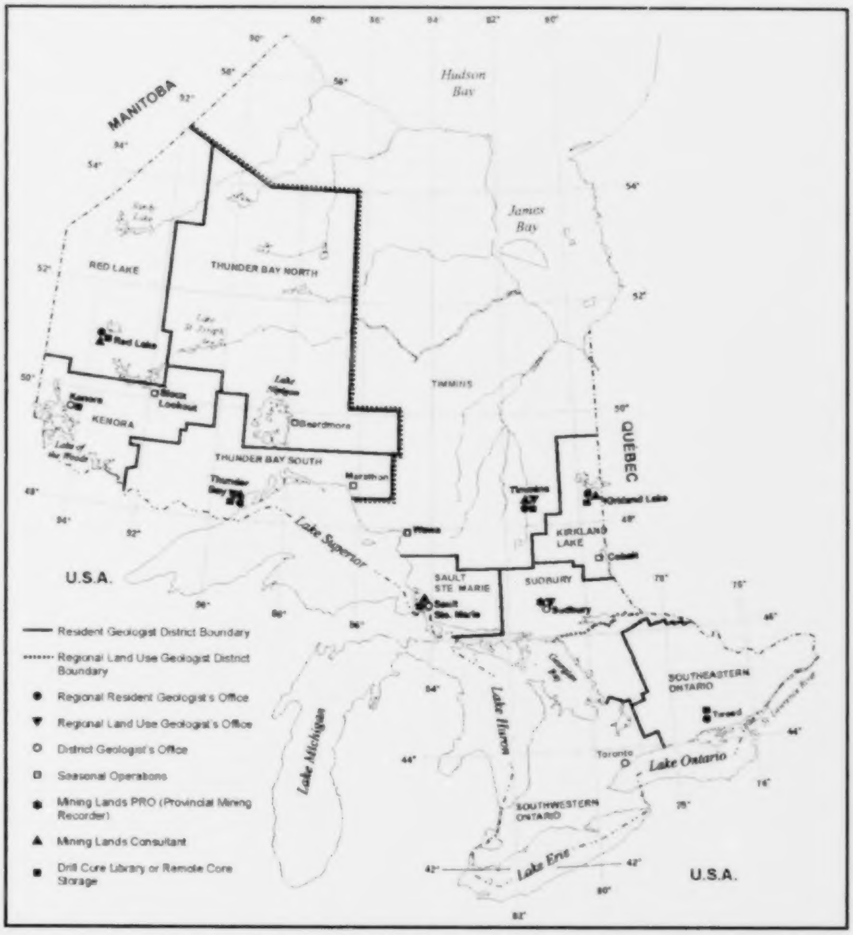
This report has not received a technical edit. Discrepancies may occur for which the Ontario Ministry of Northern Development and Mines does not assume any liability. Source references are included in the report and users are urged to verify critical information. Recommendations and statements of opinions expressed are those of the author or authors and are not to be construed as statements of government policy.

If you wish to reproduce any of the text, tables or illustrations in this report, please write for permission to the Team Leader, Publication Services, Ministry of Northern Development and Mines, 933 Ramsey Lake Road, Level B4, Sudbury, Ontario P3E 6B5.

Cette publication est disponible en anglais seulement.

Parts of this report may be quoted if credit is given. It is recommended that reference be made in the following form:

Hamilton, S.M., Hattori, K.H. and Clark, I.D. 2005. Investigation into the source of forest-ring-related natural gas in northern Ontario; *in* Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, p.19-1 to 19-4.

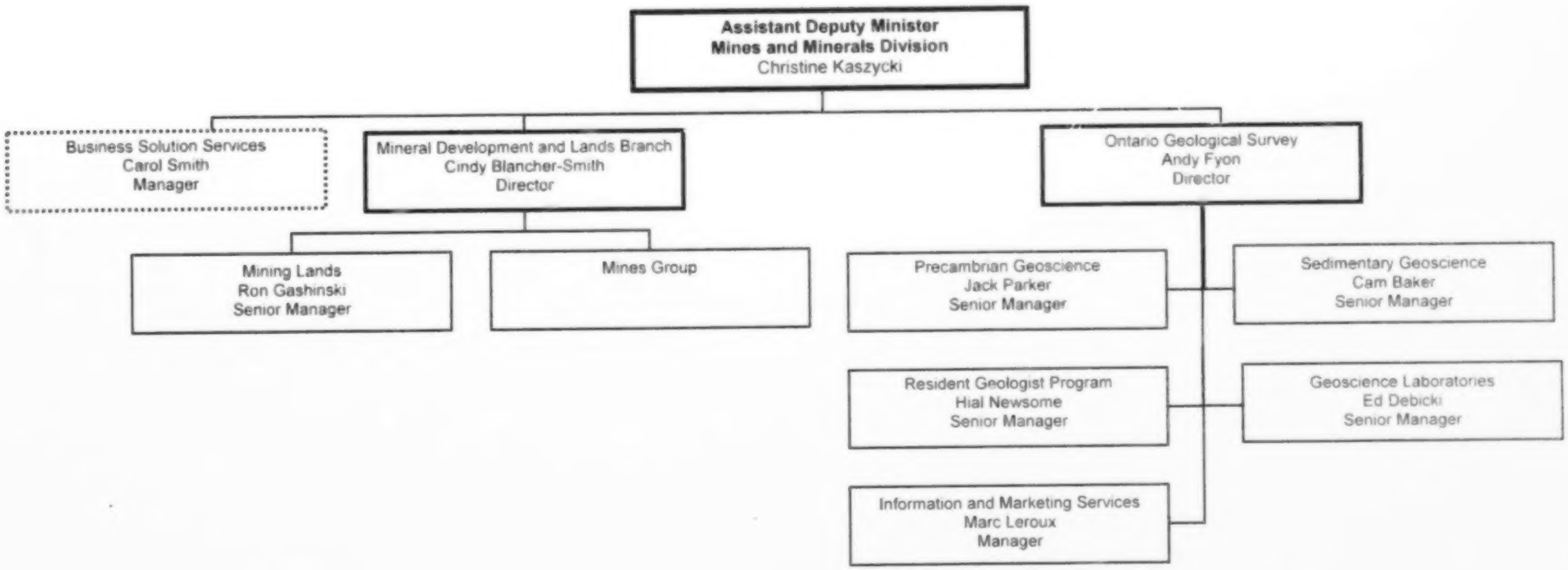

MANITOBA
Hudson Bay
James Bay
RED LAKE
THUNDER BAY NORTH
Red Lake
Kenora
KENORA
Sioux Lookout
Lake Nipigon
Beardmore
THUNDER BAY SOUTH
Thunder Bay
Marathon
Lake of the Woods
TIMMINS
Timmins
QUÉBEC
Kirkland Lake
KIRKLAND LAKE
Cobalt
Wawa
Lake Superior
U.S.A.
SAULT STE MARIE
Sault Ste. Marie
SUDBURY
Sudbury
SOUTHEASTERN ONTARIO
Tweed
Toronto
Lake Ontario
Lake Huron
Lake Michigan
SOUTHWESTERN ONTARIO
Lake Erie
U.S.A.
Resident Geologist District Boundary
Regional Land Use Geologist District Boundary
● Regional Resident Geologist's Office
▼ Regional Land Use Geologist's Office
○ District Geologist's Office
◘ Seasonal Operations
✱ Mining Lands PRO (Provincial Mining Recorder)
▲ Mining Lands Consultant
■ Drill Core Library or Remote Core Storage

Mines and Minerals Division Regional and District Offices

CITY	ADDRESS	OFFICE(S)	TELEPHONE	FAX
Kenora	Suite 104, 810 Robertson St. Kenora P9N 4J2	○ ■	(807) 468-2813	(807) 468-2930
Red Lake	Box 324, Ontario Government Building 227 Howey Street, Red Lake P0V 2M0	● ■ ▲	(807) 727-3272 (807) 727-3284	(807) 727-3553 (807) 727-3553
Thunder Bay - North	Suite B002, 435 James St. S., Thunder Bay P7E 6S7	● ■ ▼ ▲	(807) 475-1331 (807) 475-1311	(807) 475-1112 (807) 475-1124
Thunder Bay - South	Suite B002, 435 James St. S., Thunder Bay P7E 6S7	● ■ ▼ ▲	(807) 475-1331 (807) 475-1311	(807) 475-1112 (807) 475-1124
Sault Ste. Marie	Suite 200, 70 Foster Dr., Sault Ste. Marie P6A 6V8	○ ■	(705) 945-6931	(705) 945-6935
Timmins	Ontario Government Bldg., P.O. Bag 3060, Hwy 101 East, South Porcupine P0N 1H0	● ■ ▼ ▲	(705) 235-1615 (705) 235-1600	(705) 235-1620 (705) 235-1610
Kirkland Lake	10 Government Rd. E., Kirkland Lake P2N 1A2	● ■ ▲	(705) 568-4516 (705) 568-4521	(705) 568-4515 (705) 568-4515
Sudbury	Willet Green Miller Centre, Level B3, 933 Ramsey Lake Rd., Sudbury P3E 6B5	○ ✱ ▼	(705) 670-5735 (705) 670-5737	(705) 670-5681 (705) 670-5807
Tweed	P.O. Bag Service 43, 126 Old Troy Rd., Tweed K0K 3J0	● ■	(613) 478-3161	(613) 478-2873
Toronto	Mines and Minerals Information Centre, Room M2-17, MacDonald Block, 900 Bay St. M7A 1C3	○	(416) 314-3800	(416) 314-3797

Ontario Ministry of Northern Development and Mines

Mines and Minerals Division


Assistant Deputy Minister
Mines and Minerals Division
Christine Kaszycki
Business Solution Services
Carol Smith
Manager
Mineral Development and Lands Branch
Cindy Blancher-Smith
Director
Ontario Geological Survey
Andy Fyon
Director
Mining Lands
Ron Gashinski
Senior Manager
Mines Group
Precambrian Geoscience
Jack Parker
Senior Manager
Sedimentary Geoscience
Cam Baker
Senior Manager
Resident Geologist Program
Hial Newsome
Senior Manager
Geoscience Laboratories
Ed Debicki
Senior Manager
Information and Marketing Services
Marc Leroux
Manager

Contents

Office of the Director, Ontario Geological Survey

1. The Ontario Geological Survey Branch *J.A. Fyon*

2. The Far North Geological Mapping Initiative—Enhancing Northern Prosperity *J.R. Parker, C.L. Baker, J. Newsome and J.A. Fyon*

Precambrian Geoscience Section

3. Precambrian Geoscience Section—Program and Project Overview *J.R. Parker*

Abitibi

4. The Abitibi Greenstone Belt: An Update on the Precambrian Geoscience Program and the Results of the Discover Abitibi Initiative *J.A. Ayer and R. Calhoun*

5. Project Unit 05-005. General Geology of Powell Township, District of Timiskaming *B.R. Berger and S. Préfontaine*

6. Project Unit 05-005. Geology of Bannockburn and Montrose Townships, District of Timiskaming *S. Préfontaine and B.R. Berger*

7. Project Unit 05-004. Physical Volcanology and Economic Potential of Komatiite-Associated Ni-Cu-(PGE) Deposits, Bannockburn Township Area *M.G. Houlé, S. Préfontaine and B.R. Berger*

8. Project Unit 03-002. Synthesis of Archean Geology and Diamond-bearing Rocks in the Michipicoten Greenstone Belt: Results from Microdiamond Extraction and Geochronological Analyses *C. Vaillancourt, J.A. Ayer and M.A. Hamilton*

Northwestern Ontario

9. Project Unit 99-001. Precambrian Geology of the Dinorwic–Butler Lakes Area, Wabigoon Subprovince *G.P. Beakhouse*

10. Project Unit 03-011. Discrimination of Archean Domains in the Sachigo Subprovince: A Progress Report on the Geochronology *N. Rayner and G.M. Stott*

11. Project Unit 95-014. Geology and Soil Geochemistry of the Crooked Pine and Western Steep Rock Lakes Areas of the Wabigoon Subprovince: Implications for Gold Exploration *D. Stone*

Proterozoic and Grenville Province

12. Project Unit 05-002. Lake Nipigon Synthesis *T.R. Hart*
13. Project Unit 04-016. Geology and Mineral Potential of Porter and Vernon Townships, Southern Province *R.M. Easton*
14. Project Unit 05-001. 10th International Platinum Symposium: Insights Relevant to Ni-Cu-PGE Mineral Exploration in Ontario *R.M. Easton and T.R. Hart*
15. Project Unit 04-013. Timing of Gold Mineralization in the Western Grimsthorpe Domain, Central Metasedimentary Belt, Grenville Province *R.M. Easton and S.L. Kamo*

Geophysics and Information Management

16. Project Unit 00-101. Summary of Geophysical Projects and Activities *D.R.B. Rainsford and T.L. Muir*
17. Project Unit 95-024. A Re-evaluation of the RADARSAT-1 Geological Interpretation of the Lightning River Area, Abitibi Greenstone Belt, Ontario Under the Upcoming RADARSAT-2 Program (SOAR) *N.F. Trowell and Z.B. Madon*
18. Project Unit 04-019. Towards a Common Digital Data Model for Geological Mapping: Recent Developments and Issues to Address *Z.B. Madon*

Sedimentary Geoscience Section

Energy

19. Project Unit 04-025. Investigation into the Source of Forest-Ring-Related Natural Gas in Northern Ontario *S.M. Hamilton, K.H. Hattori and I.D. Clark*

Surficial Mapping and Sampling

20. Project Unit 05-019. Reconnaissance Till Sampling in the Caribou Lake Greenstone Belt Area, Northwestern Ontario *P.J. Barnett*
21. Project Unit 05-017. Regional Modern Alluvium Sampling Survey of the Gogama–Shining Tree Region, Northeastern Ontario *V.E. Felix*
22. Aggregate Resources Inventory Mapping in Ontario: A GIS-based Approach *C. Gao, F.R. Brunton, J. Shirota and S. van Haaften*

Surficial Geochemistry

23. Project Unit 05-021. Red Lake Area High-Density Lake Sediment and Water Survey, Northwestern Ontario *R.D. Dyer and S.M. Hamilton*
24. Project Unit 05-018. Gold Dispersion and Geochemical Response in Surficial Media: Implications for Data Interpretation and Exploration *R.D. Dyer*

Groundwater Program

25. Project Unit 02-018. Three-Dimensional Modelling of Quaternary Deposits in Waterloo Region, Ontario: A Case Study using Datamine Studio® Software *A.F. Bajc and M.J. Newton*

26. Project Unit 03-021. Three-Dimensional Modelling of Thick Quaternary Deposits in the Barrie Area, Central Ontario *A.K. Burt and D.F. Russell*

27. Project Unit 05-012. Karst in Southern Ontario *F.R. Brunton, J.E.P. Dodge and J. Shirota*

28. Project Unit 05-013. Bedrock Topography and Drift-Thickness Maps, Southern Ontario *J. Shirota, F.R. Brunton and R.I. Kelly*

29. Project Unit 05-011. Paleozoic Geology Map of Southern Ontario *J.E.P. Dodge, D.K. Armstrong and R.I. Kelly*

30. Project Unit 04-028. An Investigation of Buried-Valley Aquifer Systems in the Area North of Lake Ontario *S.D. Davies and S. Holysh*

31. Project Unit 04-030. Karst Delineation and Sinkhole Investigation in the Ausable Bayfield Conservation Authority Watershed and Surrounding Area *J. Hurley, A.G. Merry, F.R. Brunton, S. Wadley and D. Abbey*

32. Project Unit 05-016. Groundwater Resource Project for the Halton Area Watershed, Southern Ontario *D. Gale and P. Sarvas*

33. Project Unit 04-029. Conceptualization and Calibration of a Three-Dimensional Groundwater Flow Model for the Watersheds in Southwestern Ontario *A.G. Merry and L.P. Nicks*

Data Handling and Management

34. Project Unit 05-015. Sedimentary Geoscience Section Metadata Project *P.A. Takats, M.G. Easton, E.G. Drouin, D.J. Scholtz and J.W. Boyd*

Industrial Minerals

35. Project Unit 02-015. Regional Industrial Minerals and Diagenetic Study of the Guelph, Eramosa, and Amabel Formations, Southwestern Ontario *F.R. Brunton, L.-K. Dekeyser and M. Coniglio*

Geoscience Laboratories

36. Sample Preparation: Sample Size Considerations *J. Schweyer and E. Stairs*

Index of Authors

Metric Conversion Table

106-02079/

Office of the Director, Ontario Geological Survey

1. The Ontario Geological Survey Branch

J.A. Fyon[1]

[1]Director, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) Branch consists of five business units: Geoscience Laboratories, Information and Marketing Section, Precambrian Geoscience Section, Resident Geologist Program, and Sedimentary Geoscience Section (Figure 1.1, the OGS organizational chart).

The OGS is

- the expert provincial organization on regional to local, framework, geoscience data, information, and knowledge about Ontario;
- a principled and professional organization that operates with integrity;
- a supplier of credible and objective geoscience data and knowledge;
- a deliverer of products in a time and form that meet the client needs for quality and accuracy within the limits of our capacity and resources.

MANDATE AND CORE BUSINESS

The OGS delivers the Provision of Geoscience and Information Services Program, one of four programs under the Ministry of Northern Development and Mines' core business of Mineral Sector Competitiveness. The goal of the Mineral Sector Competitiveness core business is to enhance and to ensure the sustainable development of Ontario's mineral resources. This goal is achieved by promoting a healthy business climate that encourages and attracts mineral investment, exploration and mine development, and by undertaking targeted geoscience initiatives. OGS products stimulate investment attraction, help reduce exploration risk, are essential for informed land-use planning, and contribute to formulation of informed public policy and protection of public health and safety. Geoscience data provided by the OGS also support other government objectives, such as groundwater mapping for Safe Drinking and help contribute to the assessment of non-renewable energy potential.

PRIORITIES

This past year, the OGS focussed on several priorities. Branch cohesiveness remains a priority and branch staff and management continued to work to build on existing strengths to enhance branch-level project planning, communication and integration of activities. An OGS Branch strategic planning process, delayed because key participants were unavailable during 2004–2005, was initiated in September 2005.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.1-1 to 1-3.

© Queen's Printer for Ontario, 2005

Ontario faces some major planning and development challenges related to mineral resource access and development, groundwater resources, and security of energy supply. Consideration and incorporation of OGS geoscience data and knowledge into decision-making processes will help address these planning and development needs. To broaden the reach of OGS products and services, we continued to develop strategic relationships with several conservation authorities in southern Ontario, the Ministry of Natural Resources, Ministry of Energy, and aboriginal leaders, technical and political organizations, in addition to the mineral sector, the Federal Government agencies with an interest in geoscience, and academe.

In response to client need for accurate, accessible geoscience data in a form that can be easily searched and easily integrated into other software applications, the OGS Branch, working with Business Solutions Section, continued the deployment of GeoPortal, the Web access portal to our geoscience data and products. The OGS continued to market Ontario's mineral potential to attract new mineral investment and enhance Ontario's competitiveness and technical services available through the Geoscience Laboratories and GEO Enterprises.

The OGS continued to work in collaboration and partnership on technical (e.g., Lake Nipigon Region Geoscience Initiative, Discover Abitibi Initiative, and several conservation authorities) and communication (e.g., Eabametoong First Nation, Neskantaga First Nation, Kasabonika Lake First Nation, and Webequie First Nation) projects. We anticipate new partnerships with Natural Resources Canada–Geological Survey of Canada as part of Targeted Geoscience Initiative 3 and under Cooperative Geological Mapping Strategies Across Canada, should that federal program be funded.

OGS has a pan-provincial mandate, but Ontario's Far North represents one of our last development frontiers. In spring 2005, the Government announced the Far North Geological Mapping Initiative as a corner stone of MNDM's "Northern Prosperity Plan". A range of mapping projects and the purchase of proprietary airborne geophysical data will be initiated during the 2005–2006 fiscal year (*see* Parker et al., this volume). Because the Far North is the home of about 40 remote First Nation communities, a component of the Far North Geological Mapping Initiative includes communication, relationship-building, and partnerships with several aboriginal communities and business organizations to help raise their understanding about geoscience, the mineral industry and prospecting. These activities help lay a foundation for northern geoscience, mineral exploration, and help the aboriginal communities assess options available to support or directly participate in the mineral industry.

Challenges continue to exist, but with the input from the OGS Advisory Board, our traditional and new clients, and the continued efforts of dedicated OGS staff, the OGS Branch will continue to deliver high-quality geoscience that meets the Government priorities and stakeholder needs.

STAFF CHANGES

Following a competition in the summer 2005, J.R. Parker assumed the role of Senior Manager, Precambrian Geoscience Section.

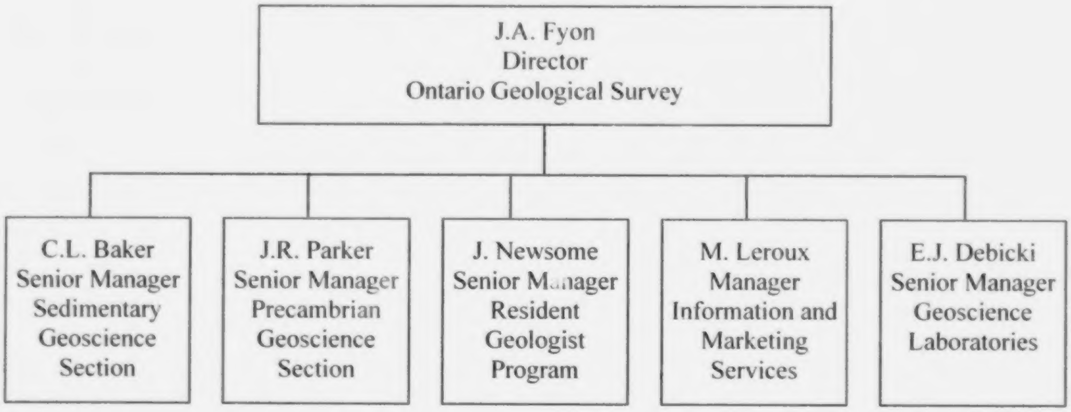

J.A. Fyon Director Ontario Geological Survey
C.L. Baker Senior Manager Sedimentary Geoscience Section
J.R. Parker Senior Manager Precambrian Geoscience Section
J. Newsome Senior Manager Resident Geologist Program
M. Leroux Manager Information and Marketing Services
E.J. Debicki Senior Manager Geoscience Laboratories

Figure 1.1. OGS organization chart.

2. The Far North Geological Mapping Initiative—Enhancing Northern Prosperity

J.R. Parker[1], C.L. Baker[2], J. Newsome[3] and J.A. Fyon[4]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Sedimentary Geoscience Section, Ontario Geological Survey
[3]Resident Geologist Program, Ontario Geological Survey
[4]Director, Ontario Geological Survey

GOAL OF THE FAR NORTH GEOLOGICAL MAPPING INITIATIVE

Recognizing the economic impact of global demand for Ontario's mineral resources and the potential for jobs and investment in new discoveries the Ontario government announced $15M over three years for geological mapping in the Far North in the 2005 Ontario Budget. This Far North initiative is also part of the Ministry of Northern Development and Mine's Northern Prosperity Plan.

The Far North Geological Mapping Initiative (FNGMI) is a a science-based, geological mapping or inventory initiative to better understand the geological history of the Far North and its mineral resources.

The geographic area to be covered by the Initiative is depicted in Figure 2.1. The general Far North region (north of 51°N latitude) includes the Ministry of Natural Resource's Northern Boreal Initiative (NBI) area. Areas where geoscience studies and mapping will be conducted will be better defined following client input and consultation with aboriginal communities.

Using state-of-the-art technologies, the FNGMI will provide independent and credible geoscience data for

- community-based land-use planning;
- private sector mineral exploration;
- policy support;
- infrastructure and other development.

The FNGMI will also engage First Nation communities to continue to enhance communication and mutual understanding, build relationships, transfer technical knowledge, build capacity and facilitate First Nations–mineral industry–Government business and other partnerships.

Summary of Field Work and Other Activities 2005
Ontario Geological Survey, Open File Report 6172, p.2-1 to 2-3.

© Queen's Printer for Ontario, 2005

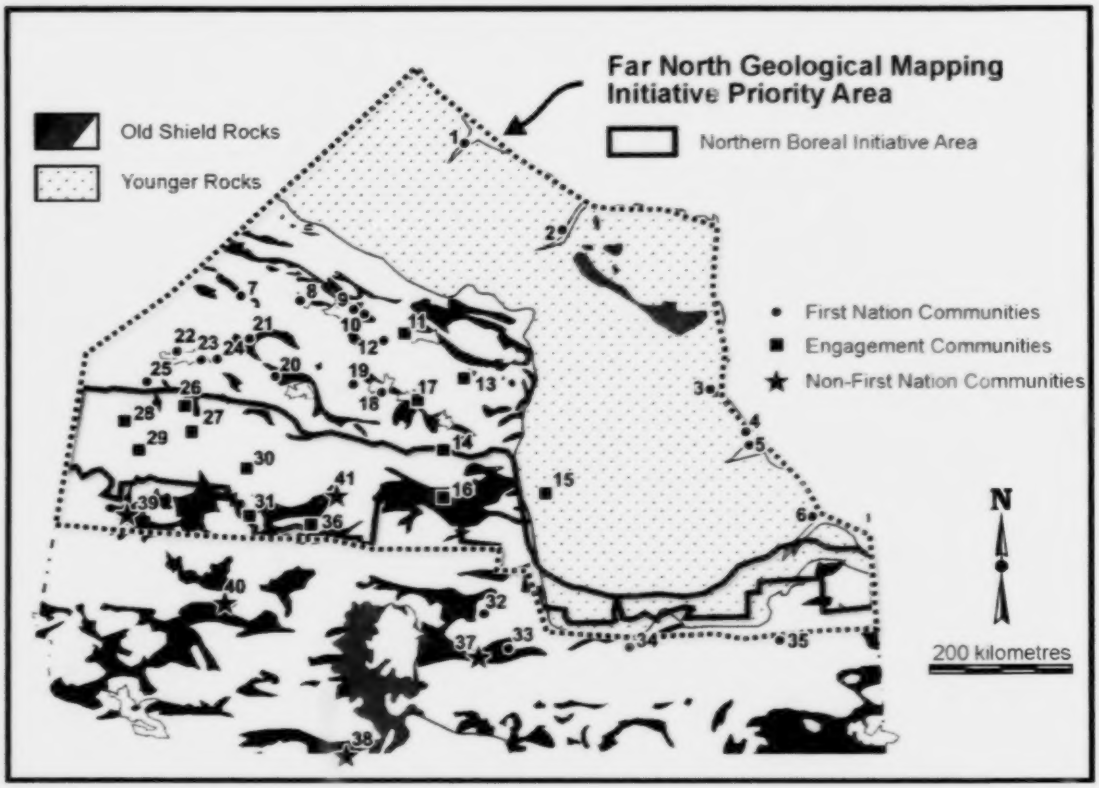
SUMMARY OF INITIATIVE COMPONENTS

Key components of the three-year Initiative include

Data Collection and Analysis: Using private-sector survey firms and Ontario Geological Survey (OGS) field crews, collect and analyze geoscience data to create new geological and mineral maps, reports and data sets, for targeted areas in the Far North. Data collection will have a focus on metallic mineral, industrial mineral, surficial material and non-renewable energy sources.

Data Delivery and Marketing: Based on the data collection and analysis, the data will be marketed to the international mineral exploration community to stimulate new investment in the Far North.

First Nation Engagement: An integral part of the Initiative involves engaging and building business relationships with First Nations in order to increase their capacity for successful business ventures with private-sector companies.


Far North Geological Mapping Initiative Priority Area
Old Shield Rocks
Younger Rocks
Northern Boreal Initiative Area
First Nation Communities
Engagement Communities
Non-First Nation Communities
N
200 kilometres
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41

First Nation Communites 1-Fort Severn, 2-Weenusk (Peawanuck), 3-Attawapiskat, 4- Kashechewan, 5-Fort Albany, 6-Moose Factory, 7-Sachigo Lake, 8-Bearskin Lake, 9- Big Trout Lake, 10-Wapekeka, 11-Kasabonika, 12-Wawakapewin, 13-Webequie, 14-Neskantaga, 15-Marten Falls, 16-Eabametoong, 17-Nibinamik, 18-Wunnumin, 19-Kingfisher, 20-North Caribou Lake, 21-Muskrat Dam, 22-Sandy Lake, 23-Keewaywin, 24- Koocheching, 25-Deer Lake, 26-North Spirit, 27-McDowell Lake, 28-Poplar Hill, 29-Pikangikum, 30-Cat Lake, 31-Slate Falls, 32-Aroland, 33-Long Lake #58, 34-Constance Lake, 35 New Post, 36-Mishkeegogamang. **Non-First Nation Communities** 37- Geraldton, 38-Thunder Bay, 39-Red Lake, 40-Sioux Lookout 41-Pickle Lake

Figure 2.1. Location of the general Far North region that will be the focus of the Far North Geological Mapping Initiative.

The mix and scale of data collection approaches under this Initiative will be finalized by the OGS after seeking advice from clients and key stakeholders. Geoscience Gap Analysis meetings will be held in Red Lake and Thunder Bay to identify geoscience gaps; identify and prioritize industry, First Nation and other user needs; identify skills, tools, methods or technologies required to address those needs; and identify possible OGS mapping project designs that may meet those needs.

Discussions will also take place with the exploration and mining sector, First Nations, the Minister's Ontario Geological Survey Advisory Board (OGSAB) as well as potential partners in the initiative.

ACTIVITIES IN 2005–2006

The following activities are presently underway as part of the Far North Initiative:

1. preparation of Requests for Proposals for the purchase of proprietary geophysical data and the acquisition of new geophysical data;
2. recruitment of staff for geoscience data compilation functions;
3. geoscience gap analysis meetings and engagement with client groups and stakeholders;
4. planning, design and preparation of mapping projects;
5. equipment acquisition;
6. information exchange and consultation with aboriginal communities.

EXPECTED RESULTS

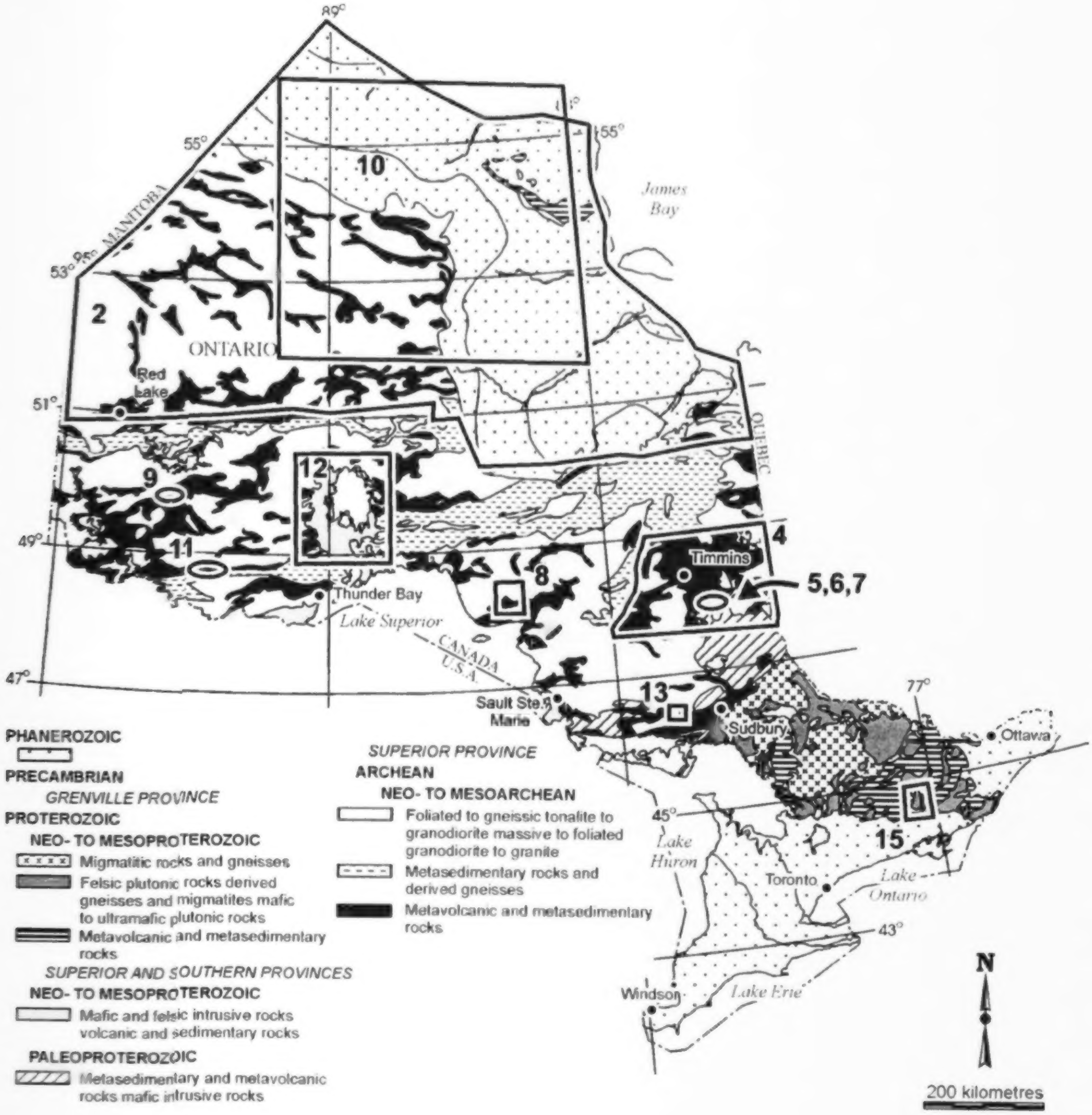
The Far North Geological Mapping Initiative will enhance Northern prosperity, lead to a better understanding of the mineral resource potential of the area and engage First Nation communities to

- attract mineral investment and jobs;
- contribute to informed land-use planning;
- help stabilize the business climate of the Far North; and
- build capacity and awareness within First Nation communities about opportunities related to the minerals and mining sector.

By 2007–2008, the Far North Geological Mapping Initiative is expected to result in the following:

- 8000–12 000 km of new "feet-on-the-ground" mapping;
- approximately 120 000 line-kilometres of new airborne geophysical surveys;
- improved understanding, and new partnerships among 6 to 12 First Nation communities, MNDM, and the private sector;
- $1–$2M in cash or in-kind contributions levered from private sector and other levels of government per year; and
- client satisfaction of 90%.

Precambrian Geoscience Section


89°
55°
55°
MANITOBA
53°
10
James Bay
2
ONTARIO
Red Lake
51°
QUEBEC
12
9
49°
11
4
Timmins
5,6,7
8
Thunder Bay
Lake Superior
CANADA
U.S.A.
47°
13
Sault Ste. Marie
Sudbury
77°
Ottawa
45°
Lake Huron
15
Toronto
Lake Ontario
43°
Windsor
Lake Erie
N
200 kilometres
PHANEROZOIC
PRECAMBRIAN
GRENVILLE PROVINCE
PROTEROZOIC
NEO- TO MESOPROTEROZOIC
Migmatitic rocks and gneisses
Felsic plutonic rocks derived gneisses and migmatites mafic to ultramafic plutonic rocks
Metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
NEO- TO MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary and metavolcanic rocks mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite massive to foliated granodiorite to granite
Metasedimentary rocks and derived gneisses
Metavolcanic and metasedimentary rocks

Location of Precambrian Geoscience Section field projects for 2004–2005. Numbers correspond to article numbers.

3. Precambrian Geoscience Section—Program and Project Overview

J.R. Parker[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

GOAL AND RESPONSIBILITY OF THE PRECAMBRIAN GEOSCIENCE SECTION

The goal of the Precambrian Geoscience Section (PGS) is to improve the understanding of Precambrian geology and metallogeny of Ontario and to convey this knowledge to clients through multi-year, multidisciplinary geoscience studies that address critical geoscience problems in key geographic areas. These studies may be delivered as part of the PGS core bedrock mapping function or through collaborative partnerships.

PGS is responsible for

- mapping of Ontario's Precambrian bedrock and understanding of various mineral deposit settings
- regional gravity, magnetic and electromagnetic geophysical data and derivative products in support of the bedrock mapping program

PRECAMBRIAN GEOSCIENCE SECTION CORE FUNCTIONS

The program direction and strategic thrusts of PGS address the mission statement and core business of the Ministry of Northern Development and Mines. Strategic thrusts (Table 3.1) are achieved through a variety of initiatives that are built upon one or more projects (Table 3.2). Therefore, project development, selection, planning and implementation are based on the strategic thrusts and initiatives in order to achieve alignment of individual projects with Ministry priorities.

The fundamental core functions of PGS projects are to

1. provide geoscience maps, reports, data, technical talks and posters, new concepts and ideas and client consultations; and
2. provide regional airborne magnetic and electromagnetic geophysical data, derivative products, and concepts and ideas based on those geophysical data to support the bedrock mapping program.

The PGS supported 43 active projects during the 2005–2006 fiscal year including 30 active core projects (*see* Table 3.2) and 13 active collaborative project agreements, which include 6 projects with the Geological Survey of Canada (Table 3.3).

In 2005, the PGS produced 14 preliminary maps, 4 open file reports and 8 miscellaneous data releases (MRDs) and 1 Miscellaneous Paper. PGS staff presented approximately 35 technical talks and 55 posters at various geoscience forums and meetings throughout the year.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.3-1 to 3-14.

© Queen's Printer for Ontario, 2005

Table 3.1. Strategic thrusts of the Precambrian Geoscience Section: 2005–2006.

Strategic Thrust	**Thrust Objective**	**Initiatives To Achieve Thrust**	**Priority Action**
1.Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces	Improve understanding of the tectonic and metallogenic evolution and mineral potential of the Superior, Grenville, and Southern provinces by integration of systematic bedrock mapping, mineral deposit studies, geological and geophysical interpretation and compilation at scales of 1:5000, 1:20 000, 1:50 000, 1:100 000, 1:250 000 and 1:2 000 000.	Provincial Initiatives	Provincial Resource Allocation: Undertake bedrock mapping and compilation augmented with mineral deposit data and geophysical interpretation of: • *non-frontier* areas and mining camps at scales of 1:20 000, 1:50 000 and 1:250 000 in the Abitibi greenstone belt and northeastern Ontario; conduct 1:50 000-scale bedrock mapping in Powell–Bannockburn–Montrose townships. • *non-frontier* areas at 1:50 000-scale in the central Wabigoon Subprovince. • *non-frontier* 1:50 000-scale mapping in Porter–Vernon townships to study a number of metal commodities including Ni-Cu-PGE; paleomagnetic discrimination of Proterozoic mafic dikes in the Uchi and English River subprovinces in collaboration with the University of Toronto.
		Abitibi Initiative	Abitibi Initiative: *Discover Abitibi*: In collaboration with Timmins Economic Development Corporation, academia and industry participate in the Discover Abitibi project through: • in-kind support by committing a portion of the PGS core bedrock mapping program to the Abitibi greenstone belt (Berger, Houlé, Trowell, Josey); • providing Senior Geoscientist (Ayer) for participation on the Discover Abitibi Technical Committee; • participate in collaborative geoscience projects • providing a Senior Geoscientist to share science leadership and project co-ordination of the Greenstone Architecture Project, which was a project awarded to Laurentian University (MERC).
		Proterozoic Initiative	Proterozoic Initiative: *Lake Nipigon Region Geoscience Initiative:* In partnership with Ontario Prospectors Association, industry, academia and other government surveys (i.e., USGS, Minnesota Survey, Geological Survey of Canada) participate by: • completing a regional synthesis of the Lake Nipigon region as part of core program; • providing Senior Geoscientists (Easton) and OGS Geophysicist (Rainsford) for participation on the Science Advisory committee; • participating in collaborative geoscience projects with academia and other government surveys; • participate in regional compilation of Mid-continent rift system with the USGS.

Table 3.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. (continued)		Metallogeny and Geology of Northwest Ontario	Metallogeny and Geology of Northwest Ontario: a) *Dryden–Wabigoon area:* Conduct bedrock mapping at 1:20 000 and 1:50 000 scales. b) *Geology of the central Wabigoon Subprovince:* Conduct bedrock mapping at 1:50 000-scale and complete synoptic report and final 1:250 000-scale bedrock compilation map.
		Initiatives with GSC	Collaborative Initiatives with Geological Survey of Canada (GSC): a) *Western Superior NATMAP and Lithoprobe initiatives:* In partnership with Geological Survey of Canada, work to complete and publish the maps and reports for the Western Superior NATMAP and Lithoprobe initiatives to resolve the distribution of old and young crust and its metallogenic significance (Stott, McIlraith). b) *Exposed Sachigo and Precambrian basement project:* In partnership with Geological Survey of Canada, to stimulate exploration and support regional-scale bedrock interpretation of northern Ontario, interpret the geology of the exposed Sachigo and the Precambrian substrate to the James Bay and Hudson Bay lowlands (Stott, McIlraith). c) *Trans-Hudson–Superior Margin Metallotect Project:* In partnership with Geological Survey of Canada and DeBeers Canada Exploration Inc. conduct geochronology and isotopic work to discriminate between Archean tectonic domains across far northern Ontario (Stott)
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or deposits types currently of interest to the mineral exploration industry.	Improve the understanding of, and mineral potential for, rocks that may contain economic concentrations of: - diamonds; - rare-metal and petalite-bearing pegmatites; - Ni-Cu-PGE; - Gold; - VMS-associated copper-zinc mineralization; and - metallic mineralization related to felsic magmatism	- Provincial-scale metallogenic inventory - Provincial-scale pegmatite mineralization - Provincial-scale diamond assessment - Documentation of magmatic nickel-copper-PGE metallogeny in Ontario	a) Document the distribution of, regional settings, and characteristics of: - Archean diamond-bearing rocks (Vaillancourt, Ayer, Stott); - Kimberlite indicator minerals and their distribution relative to major crustal structures in far northern Ontario and in northwestern Ontario (Stone); - Fractionated pegmatites and related fertile granites that may host rare-metals and petalite in Ontario (Breaks); - gold mineralization and associated alteration (Beakhouse, Berger, Easton, Ayer); - mineralized, intermediate to felsic plutonic systems (Beakhouse); - evolved (FI- to FIII-type) felsic metavolcanic rocks across the Superior Province (Hart); - by conducting on-going mapping and office-based compilations and inventories supplemented by field work (e.g., sampling and localized bedrock mapping at various scales). b) Maintain geochronology database for Ontario (Easton).

Table 3.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
3. Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-) formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.	Integrate regional geophysics into core business bedrock mapping projects.	Geophysics and Bedrock Mapping Integration Initiative	Provide on-going support of bedrock mapping and compilation projects.
			Develop new approaches, procedures and methodologies to integrate and establish geophysical component of bedrock mapping projects.
			Assess and apply new technologies for processing, interpreting and presenting geophysical data (i.e., geophysical inversion and 3D visualization software).
	Improve client awareness of, and access to, all OGS and proprietary geophysical data sets.		Maintain the Geophysical Atlas containing a graphical index of all available airborne geophysical survey information describing Ontario.
			Maintain an on-line repository (master archive) of all available airborne geophysical survey information, which will be used to seed all publications of geophysical data and which will be maintained by the OGS geophysicist.
		Geophysics and Rock Properties Data Set Initiative	Continue the implementation and development of a rock properties database as part of OGS bedrock mapping projects, i.e., recover rock density data; magnetic susceptibility data; specific gravity; establish data standards, storage format and plan.
			Acquire proprietary, multi-parameter, regional, airborne geophysical survey data.
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards and program management practices.	Implement human resource strategy by focussing on succession plans for critical positions and developing a PGS Learning Plan as required by Management Board Secretariat.	Strategic hiring and mentoring initiative to anticipate retirements of staff and loss of corporate and technical knowledge;	Address HR issues by: • Recruiting and filling the following staff vacancy: two Geoscientist-3 positions, two Geoscientist-2 positions; one Manager position subject to approval by Deputy Minister; • Developing and implementing staff technical and other training plans; • Maintaining the OGS Health and Safety manual; • Hire and train "strategically" to anticipate retirement and loss of corporate and technical knowledge; • Participate in the OGS-Branch review of the functions and responsibilities of the Geoscientist 2 and Geoscientist 3 field geologist functions.
	Complete Management Board Secretariat (MBS) mandated Program Review of geoscience program.		
	Continue to implement project management and impact assessment practices.	Support and Program Management Practices Initiative - Project and Results Management Initiative - Methods Development and Data Standards Initiative	Continue to implement and maintain project management tools and practices, including: • Project planning processes; • Track results and impacts of PGS program and provide leadership for impact of the OGS geoscience program; • Report on PGS performance measures.
	Provide staff with the Information Technology (IT) tools and operational manuals required to deliver the 2005–2006 summer field projects.		Prepare field computers in advance of staff departure.

Table 3.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
4. continued			Assess solutions for point-of-observation collection and processing of field data and begin developing a new process for collecting and digitizing field observations to streamline the workflow process for producing hard copy maps and digital data sets and creating a common archival format by: • Developing software and hardware solutions for field data collection and digitizing of geological observations; • fully integrating new solutions with current GIS data workflow; • working toward new data standards for PGS and facilitating production of hard copy maps and digital data; • purchasing software and hardware to be used for core program, pilot studies, methods development, and standards projects. Work with Information & Marketing Services and Business Solutions sections, and the rest of the OGS Branch to implement the OGS Branch information management and information technology plan by contributing staff resources as required. Apply drafting and GIS functions in support of the PGS mapping program by providing targeted staff with: • ArcGIS training for use in on-going projects; • Operational field computers and peripheral equipment; • Up-to-date digital mapping manual; Up-to-date mapping project manual.
5. Manage and maintain client, stakeholder, and First Nation relationships.	Contribute to awareness of external and internal clients and stakeholders and other ministries and governments, about the value of PGS Geoscience program, have a direct means to communicate with the PGS geoscience program, and manage PGS-related issues at as early a stage as possible. (now the role of the OGS Director)	External Committees. Internal Government committees. OGS Advisory Board and its Technical Committee and regional client association meetings. Maintain relationships and exchanging technical and administrative information with First Nation communities and organizations located in geographic areas where PGS has a geoscience program interest between now and 15 years into the future.	Client and stakeholder meetings: Represent MMD, OGS, and PGS on/at: - APGO Council – Councillor for Northeastern Ontario - Commissioner, North American Commission on Stratigraphic Nomenclature; - regional client associations; - PGS Program-level discussions with other governments; - provide administrative support to the staff and managers of the Precambrian Geoscience Section and the Sedimentary Geoscience Section. Other Ontario Government Ministries: Continue to maintain PGS program relationships with Ministry of Energy and the Ministry of Natural Resources (Peterborough, Thunder Bay regional planning unit).

Table 3.2. Precambrian Geoscience Section core projects, 2005–2006.

Initiative	Project	Project Goal	Project Status
Abitibi Initiative	Abitibi compilation – 1:250 000 compilation	Complete 1:250 000-scale stratigraphy map of Abitibi greenstone belt	On schedule for completion in 2005.
	Discover Abitibi	Participation in Technical Committee	Winding down in 2005.
	Temagami–Cobalt compilation – 1:250 000 compilation	Complete 1:250 000-scale bedrock compilation map of the Cobalt–Temagami sheet	Map to be published in 2006.
	Powell–Bannockburn–Montrose townships	Map 3 townships in Matachewan area	1:50 000 maps to be published in 2006.
	Geochemistry of Ni-Cu-(PGE) ores in the Abitibi greenstone belt	Compile a database of Ni-Cu-PGE ore compositions from the Abitibi	Database is presently being compiled.
	Shaw Dome compilation	1:50 000-scale bedrock compilation of the Shaw Dome area	Map, report, database to be published in 2006.
Proterozoic Initiative	Lake Nipigon Region Geoscience Initiative	Staff participation in Implementation and Science Advisory Committees	Winding down in 2005.
	Bedrock mapping in the Blind River–Sault Ste. Marie area	Regional mapping (1:50 000 scale) of NTS sheets 41J/5, 41J/6, 41J/11, 41J/12 41K/8 and 41K/9 with detailed mapping of selected areas of special geologic, structural or economic interest	Reconnaissance mapping started in 2005, with more detailed mapping in 2006.
	Geology and mineral potential of Grimsthorpe area, Grenville Province	1:20 000-scale bedrock mapping of parts of Grimsthorpe, Tudor, Cashel and Limerick townships	Map and report to be published in 2005–2006.
	Geology and mineral potential of eastern Tomiko terrane, Grenville Province	1:50 000-scale bedrock mapping of four 1:50 000 NTS sheets	Map and report due to published in 2006.
	River Valley bedrock compilation map	Update and add to current 1:50 000-scale compilation map	Updated map to be published in 2006.
	Lake Nipigon Region Synthesis	Report, database, 1:100 000-scale bedrock compilation of the western Nipigon Embayment	To be completed in 2006.
	Geology and mineral potential of Porter–Vernon townships	Bedrock mapping and sampling in 2005	Maps to be published in 2006.
Metallogeny and Geology of Northwest Ontario	Geology of the Wabigoon area	Map Wabigoon–Dinorwic lakes area at 1:20 000 and 1:50 000 scales	Maps to be published in 2006.
	Regional metamorphism of the Hemlo greenstone belt	1:50 000-scale map, report and database	To be published in 2006.
	Geology of central Wabigoon Subprovince: bedrock compilation of the Atikokan area	1:250 000-scale compilation	Map and report to be published in 2006.

Table 3.2. continued

Provincial-scale Metallogenic Inventory Initiative	Distribution of potentially VMS-productive felsic metavolcanic rocks	Compile locations of FI-, FII- and FIII-type rhyolites across Ontario	Project on-hold in 2005.
	Characteristics of mineralized intermediate to felsic plutonic systems	Gather/compile information on barren and mineralized felsic plutons across Ontario	On-going compilation. Report to be published in April 2006.
	Update and maintain geochronology database	Maintain up-to-date geochronology database for Ontario	On-going.
	Distribution and documentation of provincial-scale rare-element pegmatite mineralization	Document fertile peraluminous granites and related rare-element pegmatite mineralization in Ontario	On-going documentation of pegmatites. Results to be published in 2006.
Geophysics and Bedrock Mapping Integration Initiative	Geophysics integration with bedrock mapping projects	Integrate geophysics into the PGS bedrock mapping program	On-going.
Geophysics and Rock Properties Data Set Initiative	Rock Properties Project	Collect and archive rock properties data	On-going.
	Aur Resources Inc. legacy airborne geophysical surveys within the southern James Bay Lowlands	Digitally reprocess and prepare for publication	8 surveys to be released in 2006.
Support and Program Management Practices Initiative	Improving OGS Archives	Improve archives database and archiving processes	On-going.
	PGS Learning Plan – Administrative Project	Develop and commit to learning plan for PGS	On-going. Plan established for 2005–2006.
Strategic Hiring and Mentoring Initiative	Managing loss of staff, corporate and technical knowledge	Hire and train "strategically" to anticipate staff retirements	On-going.
Methods Development and Data Standards Initiative	Integrated Solution for Field Data Collection and Processing	Establish new methods for digital collection of geological data in the field; development of data model for mapping projects	On-going.
	Digital Map Standards throughout Ontario	Standardize digital map standards	On-going.
	Attributed Maps (Smart Maps) Synoptic Mapping – Abitibi Subprovince & Elsewhere	Release maps with database attached	Project on hold in 2004.
External/internal committees; OGS Advisory Board; First Nations	On-going maintenance of relationships and exchange of information with clients, stakeholders and First Nations	Ensure external and internal clients and stakeholders are aware of the value of the PGS geoscience program	On-going.

Table 3.3. Precambrian Geoscience Section collaborative projects, 2005–2006.

Initiative	**Project**	**Project Collaborator (s)**	**Project Progress**
Abitibi Initiative	Discover Abitibi – Greenstone Architecture Project	MERC-Laurentian University; University of Ottawa; University of Wisconsin – Oshkosh; Geological Survey of Canada; Consultants	Completed. Some activities related to wrap up.
	Discover Abitibi – Greenstone Architecture Project: Nickel Subproject	MERC-Laurentian University	Completed. Some activities related to wrap up.
Provincial-scale Metallogenic Inventory Initiative	Characteristics of mineralized intermediate to felsic plutonic systems	Placer Dome Inc. - Australia	Underway with results to be published in 2006.
Proterozoic Initiative	Midcontinent Rift Compilation	United States Geological Survey; Minnesota Geological Survey	On-going.
	Lake Nipigon Region Geoscience Initiative	Ontario Prospectors Association; Lakehead University; Geological Survey of Canada; University of Alberta	Completed. Some activities related to wrap up.
	Composite Arc Belt Geochronology Compilation	University of Alberta, Royal Ontario Museum	On-going.
	Paleomagnetic discrimination of Proterozoic dike swarms in the English River and Uchi subprovinces	University of Toronto	On-going. Project delayed in 2005.
Collaborative Projects with the GSC: Far North Initiative	Reprocessing and interpretation of ODM–GSC geophysics of exposed Archean in Sachigo Subprovince	Geological Survey of Canada	On-going.
	Reprocessing and interpretation of ODM–GSC geophysics of Proterozoic Substrate, James Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in April 2006.
	Reprocessing and interpretation of ODM–GSC geophysics of Archean Substrate, Hudson Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in 2007.
Collaborative Projects with the GSC: Trans-Hudson–Superior Margin Metallotect Project	Discrimination of Archean tectonic domains across northwestern Ontario, north of 52°	Geological Survey of Canada; DeBeers Canada Exploration Inc.	Plan to complete in 2006.
Western Superior Lithoprobe Initiative	Western Superior Lithoprobe Transects – reflection seismic transect routes	Geological Survey of Canada and various universities	On-going.
Collaborative Projects with the Geological Survey of Canada (GSC): Western Superior NATMAP and Lithoprobe Initiatives	Regional metallogeny of northwest Superior Province	Geological Survey of Canada	Metallogenic maps to be completed by OGS.

PROGRAM DIRECTION: STRATEGIC THRUSTS

Core Bedrock Mapping and Geophysics Program

The PGS Strategic Thrusts (*see* Table 3.1) are derived from the Ministry business goals articulated in the Northern Prosperity Plan (NPP) which is derived from the Government's 5 major priorities:

- student success;
- healthier Ontarians;
- prosperity for people;
- strong communities; and
- stronger democracy.

The purpose of PGS Strategic Thrusts is to focus skilled staff and resources in key geological areas or geoscience themes, over a period of 3 to 5 years, to contribute to the goals of the NPP, which include expanding our geoscience expertise; supporting sustainable development and effective land-use planning; attracting new mineral investment; building new partnerships with Aboriginal communities, private sector and federal government; and collaborating with other ministries on horizontal initiatives.

The PGS program is organized into 5 technical or administrative Strategic Thrusts:

1. Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces.
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or mineral deposit types that are currently of interest to the mineral exploration industry (e.g., potential diamond-bearing rocks, gold mineralization, rare-element and/or petalite-bearing pegmatites, nickel-copper-platinum group element (PGE) mineralization and volcanogenic massive sulphide (VMS) mineralization) or may be of interest in the future.
3. Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-) formatting, organization and delivery of all available OGS and proprietary geophysical information; provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards, measurement of program results and impact and program management practices.
5. Develop and manage client and stakeholder relationships by: providing a liaison role, representation, or support on behalf of the PGS on client committees, regional client association meetings, inter-Ministry committees and formal or informal working groups; and committees or working groups associated with professional or learned associations. Maintaining relationships and exchanging technical and administrative information with First Nation communities and organizations located in geographic areas where PGS specifically has a geoscience program interest between the present and 15 years into the future.

These strategic thrusts are addressed through a series of initiatives, built upon one or more projects. The purpose of the strategic thrusts is to focus PGS staff and resources in key geological areas to address the priorities and needs of the initiative. In addition, PGS participates in several collaborative projects to complement existing PGS staff skills and capacity and to expand the amount of geoscience data available that describe Ontario. Collaborative projects are an important means to extend scarce government resources and to capitalize on resources and expertise available in other government geological surveys, universities or industry.

PROJECT PLANNING, MANAGEMENT, AND CONSULTATION PROCESS

PGS management and staff conducted planning and project management processes and practices to deliver 43 geoscience projects conducted by core staff and in collaboration with partners. Information required to describe projects, monitor and adjust progress, and assess their impact on the minerals industry is collected and analyzed to assess achievement of program goals.

To formulate and discuss project plans for summer of 2005 and to begin development of summer 2005 project plans, PGS staff were involved in several consultations with regional client associations:

- February 2005: Ontario Geological Survey Advisory Board Technical Committee
- March 2005: Southern Ontario Prospectors Association, Tweed
- June 2005: Porcupine Prospectors and Developers Association, Timmins; Sudbury Prospectors and Developers Association, Sudbury; the Sault and District Prospectors Association, Sault Ste. Marie; and the Northern Prospectors Association, Kirkland Lake.

NEW PROJECTS

The following new technical projects will be operational and will require resources of the PGS during the 2005–2006 fiscal year:

- PGS staff are involved in an Ontario Geological Survey–Placer Dome Inc. collaborative project to better understand the relationships between gold mineralization and intermediate to felsic plutons in the Superior Province with emphasis on the Abitibi and Red Lake greenstone belts.
- PGS staff and Dr. Peter H. Thompson are also involved in a study of the regional metamorphic history of the Hemlo greenstone belt to better understand the relationship of metamorphism to gold mineralization in the belt.

ADD-ON PROGRAMS

PGS staff and management collaborated with other OGS staff to plan and initiate 1 significant add-on geoscience programs:

- The Far North Geological Mapping Initiative (PGS began planning and implementation of bedrock mapping and geophysical data acquisition) (Parker et al., this volume).

PRECAMBRIAN GEOSCIENCE SECTION INITIATIVES

PGS initiatives are based on geographic or functional groupings and are made up of 1) team initiatives (i.e., Abitibi Initiative) consisting of individual projects that are designed to meet an overall goal; 2) inter-jurisdictional team initiatives, such as Western Superior NATMAP, that consist of individual and joint Ontario Geological Survey (OGS) and Geological Survey of Canada (GSC) projects that are also designed to meet an overall goal or objective; and 3) individual, focussed projects. The major initiatives of the PGS are subdivided into 6 broad categories outlined below and in Table 3.2 and Table 3.3.

1. Initiatives that involve collaborative project agreements with the Geological Survey of Canada (GSC):
    - Western Superior NATMAP and Lithoprobe mainly focussed in north and northwest Ontario;
    - The Sachigo Subprovince and the Hudson and James Bay Lowlands;
    - The Trans-Hudson–Superior Margin Metallotect Project.
2. Initiatives involving provincial-scale metallogenic compilation and inventory studies:
    - Documentation of specific types of mineralization;
    - Inventories of various tectonic settings relevant to mineral exploration.
3. Initiatives based on geographic area:
    - Abitibi initiative;
    - Metallogeny and geology of northwest Ontario;
    - Proterozoic initiative.
4. Initiatives involving support of the PGS program:
    - Support to program management practices;
    - Project and results management;
    - Methods development and data standards;
    - Strategic hiring and mentoring.
5. Initiatives involving geophysical projects:
    - Geophysics and bedrock mapping integration initiative
    - Geophysics and rock properties data set initiative.
6. Initiatives that develop and manage client, stakeholder and First Nation relationships:
    - External and internal committees;
    - Regional associations and participation at meetings of OGS Advisory Board and its Technical Committee;
    - Maintaining relationships and exchanging technical and administrative information with First Nation communities.

Collaborative Projects with the Geological Survey of Canada

Products from the Western Superior NATMAP initiative continued to be developed in 2005. PGS staff participated in the production of a digital data compilation (CD-ROM) for the Wabigoon Subprovince. Interpretation of the Lithoprobe reflection seismic transect routes across the Western Superior Province continued in 2005 under the Western Superior Lithoprobe initiative.

G.M. Stott continued work on the geological interpretation of the Archean and Proterozoic substrate below the Phanerozoic cover of the James Bay and Hudson Bay lowlands and the exposed Archean in the Sachigo Subprovince as part of an Ontario Geological Survey–Geological Survey of Canada Collaborative Project Agreement. The interpretation is using reprocessed ODM–GSC airborne geophysical data and proprietary geophysical data purchased under the Operation Treasure Hunt initiative. The project will 1) compile geoscience data for the James Bay–Hudson Bay lowlands in order to provide an interpretation of bedrock features beneath the Phanerozoic cover; 2) produce 3, 1:500 000-scale geological maps in hard-copy and digital formats. The James Bay Lowlands sheet is scheduled for release in early 2006.

A project was initiated in 2004 to discriminate between Archean tectonic domains across northwestern Ontario as part of the lowland work described above and the Trans-Hudson–Superior Margin Metallotect Project with the GSC (Rayner and Stott, this volume). The project is a collaboration between the Ontario Geological Survey, DeBeers Canada Exploration Inc. and the Geological Survey of Canada. The project consists of sampling outcrops and diamond-drill core for geochronology and Nd and Hf isotopic characterization. The results will be used to assist in subdividing the most northern part of the Superior Province in Ontario into tectonic domains of contrasting age and tectonic development.

Provincial-Scale Metallogenic Compilation and Inventory Studies

The PGS continued on-going, multi-year, province-scale projects that fall under the initiative to create inventories of various tectonic settings relevant to mineral exploration, such as 1) the documentation and distribution of FI-, FII- and FIII-type, potentially volcanogenic massive sulphide deposit (VMS)-productive felsic metavolcanic rocks; 2) a rare-element pegmatite characterization project to study rare-element mineralization; 3) characteristics of mineralized intermediate to felsic plutonic systems; and 4) update and maintain the geochronology database for Ontario.

Initiatives Based on Geographic Area

The Abitibi Initiative includes 4 core business, mapping projects (*see* Table 3.2) (Ayer and Calhoun, this volume), including the 1:250 000-scale stratigraphic map of the Abitibi greenstone belt.

J.A. Ayer is the PGS representative on the Discover Abitibi Technical Committee. The Discover Abitibi Initiative was completed in 2005 with wrap-up of geoscience reports, maps and data under the Greenstone Architecture Project. This project was awarded to the Mineral Exploration and Research Centre (MERC)–Laurentian University and involved an international multi-disciplinary science team. J.A. Ayer shared science leadership and project co-ordination with MERC–Laurentian University staff for the Greenstone Architecture Project.

The geology and metallogeny of Northwest Ontario initiative currently includes 2 core projects:

- geological mapping in the Dryden–Wabigoon area (Beakhouse, this volume);
- a 1:250 000-scale compilation of the Atikokan area resulting from 5 years of bedrock mapping in the central Wabigoon Subprovince (Stone, this volume);

The Proterozoic initiative includes several projects such as

- 1:20 000-scale bedrock mapping in Porter and Vernon townships, west of Sudbury (Easton, this volume).
- Paleomagnetic discrimination of Proterozoic dike swarms in the English River and Uchi subprovinces, which is an Ontario Geological Survey–University of Toronto Collaborative Project Agreement (Halls, Stott, and Davis 2005).
- A continuation of a compilation of the geology of the Mid-Continent Rift conducted in collaboration with the United States Geological Survey and the Minnesota Geological Survey.

The Proterozoic initiative also includes the Lake Nipigon Region Geoscience Initiative (LNRGI) which was completed in 2005. PGS staff are completing a regional synthesis of the Lake Nipigon region (Hart, this volume) as part of the PGS core program.

Initiatives Involving Geophysical Projects

Several geophysical projects and activities are described in detail in Rainsford and Muir (this volume). Integration of geophysics into the bedrock mapping projects continues with many geoscientists routinely using hand-held magnetic susceptibility meters during mapping as well as a variety of geophysical data and derived products for interpretation.

Modelling of magnetic data has been facilitated by the use of magnetic susceptibility data now routinely collected as part of the bedrock mapping program. Smooth model inversion software and other simpler and faster modelling tools have been acquired to provide insight into specific mapping problems.

Technical support was provided to the Discover Abitibi and LNRGI initiatives as part of in-kind support by the PGS.

INTER-JURISDICTIONAL AND COMMITTEE REPRESENTATION

PGS staff represented the Ontario Geological Survey on several inter-jurisdictional committees, internal committees and associations during the 2005 to 2006 fiscal year, including

1. Commissioner, North American Commission on Stratigraphic Nomenclature
2. APGO Councillor for Northeastern Ontario
3. Discover Abitibi Technical Committee
4. MNDM Health & Safety Committee
5. Ontario Association of Remote Sensing
6. MSc committees at Laurentian University
7. Lake Nipigon Region Geoscience Initiative
8. Institute on Lake Superior Geology

STAFFING CHANGES IN THE PRECAMBRIAN GEOSCIENCE SECTION

J.R. Parker accepted the position of Senior Manager for the PGS in September 2005. Several staff, as part of a management training and development opportunity, were acting in the position of Manager, Bedrock Mapping and Geophysics.

C.A. MacDonald and E. Tremblay left the PGS at the termination of the Lake Nipigon Region Geoscience Initiative in March 2005. L.A.F. Hall and C. Vaillancourt also left the PGS in April and June 2005, respectively.

M.D. Young accepted a position with the PGS as Precambrian Geoscientist in September 2005 to conduct bedrock mapping in the Far North of Ontario.

REFERENCES

Halls, H.C., Stott, G.M. and Davis, D.W. 2005. Paleomagnetism, geochronology and geochemistry of several Proterozoic mafic dike swarms in northwestern Ontario; Ontario Geological Survey, Open File Report 6171, 59p.

4. The Abitibi Greenstone Belt: An Update on the Precambrian Geoscience Program and the Results of the Discover Abitibi Initiative

J.A. Ayer[1] and R. Calhoun[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Timmins Economic Development Corporation, Discover Abitibi Initiative, Timmins, Ontario

INTRODUCTION

This report summarizes the results of 2 distinct programs, both designed to stimulate exploration and development in the Abitibi greenstone belt (ABG) in Ontario. The first part provides an update on the Precambrian Geoscience Section program (*see* Parker, this volume) of the Ontario Geological Survey (OGS) within the northeastern part of Ontario. The second part of the report summarizes progress and results of the Discover Abitibi Initiative (DAI), a $12 million exploration-focussed, geoscience data acquisition and legacy data compilation project collaboratively funded with Provincial, Federal and private sector contributions.

PRECAMBRIAN GEOSCIENCE SECTION PROJECTS

To date, the multi-year Abitibi compilation project, being done by J.A. Ayer and N.F. Trowell, has produced 5 hard-copy and digital versions of the Timmins, Lake Abitibi, Kirkland Lake, Swayze and Matachewan map areas at a scale of 1:100 000. Within the past year, we have also released an updated 1:250 000 scale hard-copy and digital compilation map covering all the above map areas (Ayer, Trowell and Josey 2004; Ayer, Berger et al. 2005). This past summer, work began on a new 1:100 000 scale compilation map covering the Cobalt–Temagami area with both a hard-copy and digital map to be released in 2006. These products, in conjunction with new geochronological and lithogeochemical sampling, will enable further review and refinement of lithotectonic assemblages and the timing of mineralization; establishment of a more formalized stratigraphy; and the erection of new metallogenic and geodynamic models for the evolution of the AGB (Ayer, Amelin et al. 2002; Ayer, Thurston et al. 2005). J.A. Ayer is also the Ontario Geological Survey's representative on the Technical Committee of the Discover Abitibi Initiative and is the co-ordinator for the Greenstone Architecture Project (described below). Time spent on this project represents another in-kind contribution by the OGS to DAI.

M.G. Houlé is currently working on a 1:50 000-scale compilation project in the Shaw Dome area south of Timmins (Figure 4.1). The project is funded by the OGS, but also provides in-kind support for the Greenstone Architecture Project of the DAI to better understand the role of nickel-copper-platinum group elements (Ni-Cu-PGE) mineralization in the metallogenic evolution of the AGB (discussed further in "Greenstone Architecture Project"). The project provides a follow-up for the bedrock mapping of Deloro, Shaw, Eldorado, Adams, Carmen and Langmuir townships (Houlé and Guilmette 2004). The 4 major goals of this project are to 1) to clarify lithologic uncertainties and to refine lithologic and assemblage boundaries; 2) to better understand the stratigraphic and structural nature of the Shaw Dome;

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.4-1 to 4-11.

© *Queen's Printer for Ontario, 2005*

3) to evaluate the mineral potential of the area; and 4) to study the ultramafic metavolcanic and intrusive rocks. A close spatial relationship between extrusive and intrusive ultramafic rocks and sulphide-bearing iron formation occur extensively along the margins of the Shaw Dome. The combination of abundant olivine cumulate (i.e., high magma flux) and its proximity to sulphide-bearing iron formation (i.e., a sulphur source) results in high prospectivity for komatiite-associated Ni-Cu-PGE deposits as is indicated by the presence of a number of past-producing nickel-copper mines in the map area. Products to be released as part of this project in 2006 include a 1:50 000 scale map, an Open File Report and a Miscellaneous Release—Data.

M.G. Houlé is also completing a PhD thesis focussed on the facies relationships of komatiite occurrences associated with Ni-Cu-PGE deposits in the AGB. To further this research, and in order to assist the bedrock mapping project in the Matachewan area (see below), Michel has examined and reports on a number of komatiite occurrences and their associated mineralization in the Matachewan area (Houlé, Préfontaine and Berger, this volume).

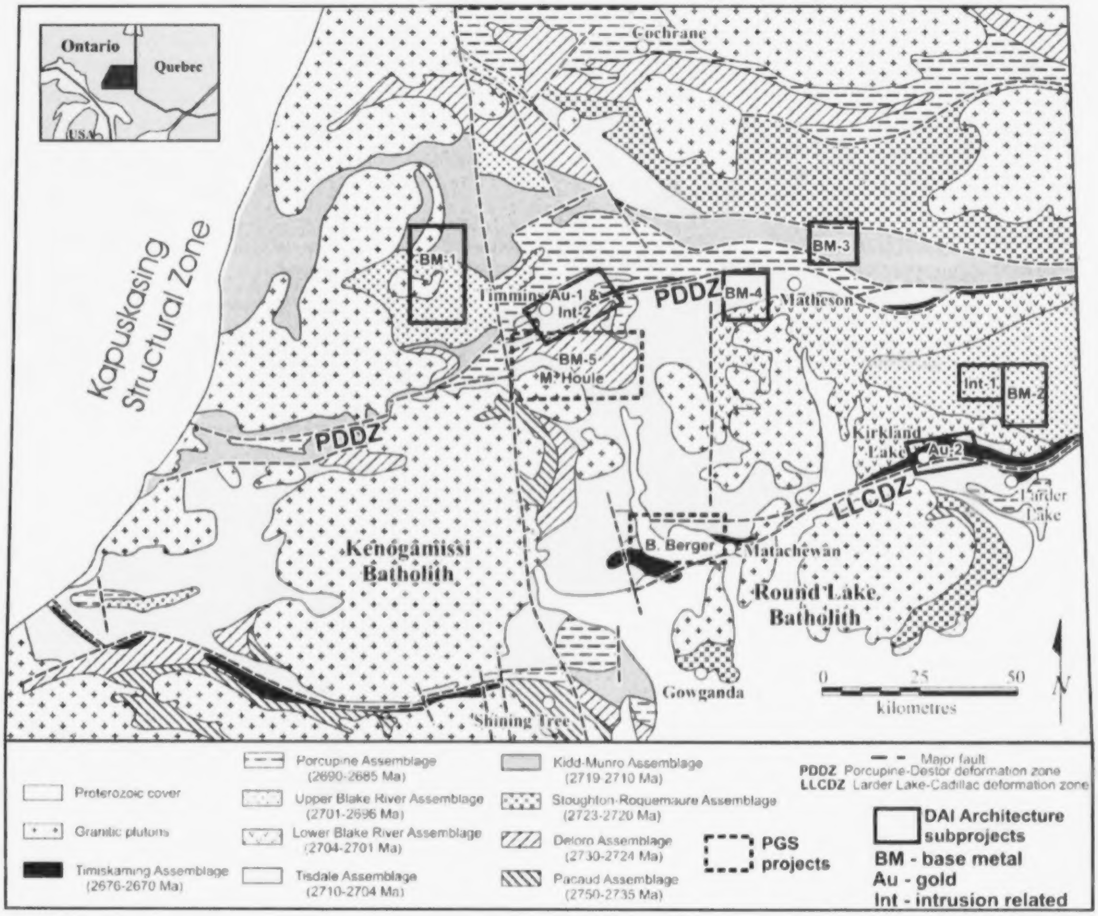

Ontario
Quebec
USA
Cochrane
Kapuskasing Structural Zone
BM-1
BM-3
Timmins
Au-1 & Int-2
PDDZ
BM-4
Matheson
BM-5
M. Houle
Int-1
BM-2
PDDZ
Kirkland Lake
Au-2
Larder Lake
LLCDZ
B. Berger
Matachewan
Kenogamissi Batholith
Round Lake Batholith
Gowganda
Shining Tree
0
25
50
kilometres
N
Proterozoic cover
Granitic plutons
Timiskaming Assemblage (2676-2670 Ma)
Porcupine Assemblage (2690-2685 Ma)
Upper Blake River Assemblage (2701-2696 Ma)
Lower Blake River Assemblage (2704-2701 Ma)
Tisdale Assemblage (2710-2704 Ma)
Kidd-Munro Assemblage (2719-2710 Ma)
Stoughton-Roquemaure Assemblage (2723-2720 Ma)
Deloro Assemblage (2730-2724 Ma)
Pacaud Assemblage (2750-2735 Ma)
PGS projects
Major fault
PDDZ Porcupine-Destor deformation zone
LLCDZ Larder Lake-Cadillac deformation zone
DAI Architecture subprojects
BM - base metal
Au - gold
Int - intrusion related

Figure 4.1. Assemblage map for the Ontario portion of the Abitibi greenstone belt with locations of the Precambrain Geoscience Section project areas and subproject areas for the Greenstone Architecture Project of the Discover Abitibi Initiative (*modified after* Ayer, Thurston et al. 2005).

B.R. Berger and S. Préfontaine mapped Powell, Bannockburn and Montrose Townships at 1:20 000 scale west of Matachewan (*see* Figure 4.1). This project extends westward the multi-year mapping done along Highway 66 from Swastika to Matachewan, which resulted in 8 townships being mapped at 1:20 000 scale over the last 4 years (*see* Berger 2004). The close proximity of the map area to the Kirkland Lake and Matachewan gold camps emphasizes the need to advance our knowledge of the geology of this area. Additional products to be released from this project in 2005 or 2006 include a 1:50 000 synoptic map and an Open File Report.

This summer's mapping (*see* Berger and Préfontaine, this volume) indicates that there are three environments that host the bulk of the gold mineralization in Powell Township. The first is the mineralization at the Young–Davidson and Consolidated Matachewan mines, which display a strong association with syenite, but also indicates that many ore zones are structurally controlled by folding and the L_2 lineations. The second mineralized environment occurs along the contact between komatiitic flows and clastic metasedimentary rocks. Numerous gold showings occur at or near this contact throughout the township. The third mineralized environment is exemplified by the Oka occurrence where mineralization is associated with komatiitic and mafic metavolcanic flows in sheared contact with clastic metasedimentary rocks and recrystallized pyrite-magnetite iron formation.

This summer's mapping in Bannockburn and Montrose townships indicate that both Ni-Cu-(PGE) and gold are important base and precious metal commodities in this area (*see* Préfontaine and Berger, this volume; Houlé, Préfontaine and Berger, this volume). Newly discovered relatively high-grade Ni-Cu mineralization occurs at the bottom of an ultramafic unit (the C-zone) in the western part of Bannockburn. Thus, it is recommended that the area be explored in more detail. The C-zone is coincident with a magnetic high that is perpendicular to the main magnetic trend in this area. Perhaps, other magnetic highs perpendicular to the regional trend may bear Ni-Cu mineralization as well. Several gold showings are found in the northwestern part of Bannockburn Township and northeastern part of Montrose Township including the past-producing Ashley mine. All the showings are in quartz veins accompanied by iron carbonate alteration. Widespread carbonate alteration and quartz veining indicates more exploration is warranted in this area.

An increase in the number and significance of diamond discoveries in Archean rocks of the Michipicoten greenstone belt of the Wawa Subprovince in the last few years has resulted in rising interest in diamond exploration in the Wawa area. Bedrock mapping, at a scale of 1:20 000, was done in Menzies and Musquash townships (Vaillancourt et al. 2004). The results of this mapping and new geochronological data that indicates the diamondiferous heterolithic breccias are diatremes (typically with the highest diamond content) and are coeval with the diamondiferous lamprophyre dikes, both being about 20 million years younger than the metavolcanic host rocks of the Catfish assemblage (ca. 2700 Ma). Additional study on specific samples (Vaillancourt, Ayer and Hamilton, this volume) indicate that the diamonds are not restricted to a single rock type unit because microdiamonds were obtained from heterolithic breccia both with and without ultramafic clasts, and from a fragment-free ultramafic dike. The largest stones were recovered from the ultramafic dike at the Genesis occurrence.

THE DISCOVER ABITIBI INITIATIVE

The Discover Abitibi Initiative (DAI) is an exploration-focussed, geoscience data acquisition and legacy data compilation project that commenced with the acquisition phase in 2003. During the period of study, new geoscience information was collected and delivered to the exploration industry to stimulate exploration and development in the western Abitibi greenstone belt. This high mineral potential greenstone belt has been the source of exceptional mineral wealth for Ontario and is internationally recognized as a signature site for further mineral development.

The Timmins Economic Development Corporation (TEDC) has taken the role of lead agency during the initiative and has collaborated with the mineral industry as well as the federal, provincial and municipal governments to foster partnerships, to develop an atmosphere of mutual respect and to reach a common goal. The initiative has received a total of $12 million in funding from FedNor (Industry Canada), the Northern Ontario Heritage Fund Corporation, private sector partners, service industry partners and individuals. In-kind support was received from the Ontario Geological Survey, the Geological Survey of Canada and the mining industry. Proprietary data from industry valued at greater than $22 million was incorporated into the released data sets. Additional data is being incorporated into some of the final data releases and the total value for in-kind information is expected to exceed $35 million.

Framework of the Initiative

The initiative was based on a program within FedNor (Industry Canada) in which funding became available to address the issue of single industry or resource communities experiencing a major downturn in their economies. An initial meeting resulted in the formation of the present structure of the initiative. The TEDC is the contractual manager of the project. A DAI management committee, a technical committee and an advisory board provide support for the TEDC board of directors in the technical aspects of the project. The committees comprise mineral explorationists from the local prospectors associations, mining companies, private consultants and each committee has government representatives in an advisory capacity. The exploration community, individuals and universities submitted the proposals, which were then evaluated and ranked by the technical committee on the basis of their capability to fill knowledge gaps, to expand the understanding of the greenstone belt from areas of intense exploration into areas covered by overburden and to use new technologies in the search for new mineral deposits. In addition, DAI has drawn upon the expertise of the Ontario Geological Survey and the Geological Survey of Canada for advice and direction.

The Importance of the Initiative

Collaborative initiatives such as the Discover Abitibi Initiative are extremely important to the well being of mining in Ontario and Canada. Sharing the high cost of geoscience programs is becoming increasingly important as governments try to reduce their overall costs. The mining industry is one of the major driving forces of the Canadian economy. In 2004, the mineral and mineral processing industries contributed $41.8 billion dollars to the Canadian economy, equal to 4% of the national Gross Domestic Product. It represented 13.8% of our total exports, employed 369 420 Canadians, often in rural, remote, northern and Aboriginal communities, invested $333 million in new technologies from exploration to final processing, and accounted for 75% of the total volume handled at Canadian ports and 60% of the rail freight. The mining industry in Ontario represents a significant portion of the above total. Within the region of Timmins–Kirkland Lake, the importance of this contribution is even higher because of the relative importance of resource-based industries.

The method employed to carry out the initiative from the grassroots up was very important in its success. The value of the process was in soliciting input from locally based expertise, bringing together like-minded individuals and using innovative techniques in the search for better ways to find mineral deposits. The Abitibi greenstone belt is a world-renowned mining area and remains one of the best target areas for mineral exploration. Providing new geoscience information which helps to fill existing knowledge gaps will encourage additional exploration and will help find new mines to re-invigorate the mining industry in northeastern Ontario.

Objectives of the Initiative

The objectives set out for the initiative are to

- identify local and regional geoscience knowledge gaps
- provide data, information, knowledge and innovative models to the mining industry
- demonstrate the value and the potential for investment in the Discover Abitibi region
- market and encourage the mineral industry to invest in the Discover Abitibi region and, thus, increase current stakeholder's value
- position the Discover Abitibi region as a premier place for investment through community leadership

In addition, the Discover Abitibi Initiative hopes to increase the rate of discovery in the region by addressing issues such as extensive overburden cover and the potential for deep orebodies by

- improving or developing targeting and screening techniques
- removing technical and knowledge impediments to investment
- helping the exploration community apply best practices
- helping the labour force in the region acquire and market global technical skills
- providing a mechanism to attract discretionary global exploration dollars to the Discover Abitibi region.

Results to Date

To date, the DAI has achieved the following results:

- relevant high-quality geoscience data has been provided to meet the needs of the exploration community
- staking activity in the region has increased by 14 000 units in the surveyed areas, this increase is particularly evident in the areas covered by the MegaTEM and high-resolution magnetometer surveys
- exploration expenditures have increased and several companies that are newcomers to the Abitibi greenstone belt are now active in the region
- the first DAI result-based "discovery" was announced by Tres-Or Resources in 2005. Based on a high-resolution magnetometer survey, they discovered a 20 ha diamondiferous kimberlite pipe within the Round Lake Batholith southwest of Kirkland Lake
- the number of active claims has steadily increased during the period of the initiative.

In the medium and long term, based on developments to date, the following results are expected:

- increase in mineral expenditures will continue
- exploration companies will be able to fund and advance projects more rapidly
- communities in the DAI area will benefit from higher employment levels with related spin-off economic benefits
- stabilization of the local and regional economies
- additional long-term economic benefits if an ore deposit is discovered for both the region and for Ontario.

Geoscience Projects

As of October 1, 2005, the following projects have been completed with numerous products released to the public through the OGS. Airborne geophysical survey coverage under DAI is shown on Figure 4.2.

Four MegaTEM II surveys were flown: the Timmins survey, located north of the city of Timmins; the Kamiskotia survey; the Halliday Dome survey; and the Kidd–Munro – Blake River survey. Fugro Airborne Surveys also donated 2800 line kilometres of data covering gaps within the Kidd–Munro – Blake River survey area. In addition, an AeroTEM survey donated by Outokumpu Mines over the Shaw Dome area was reprocessed and released to the public.

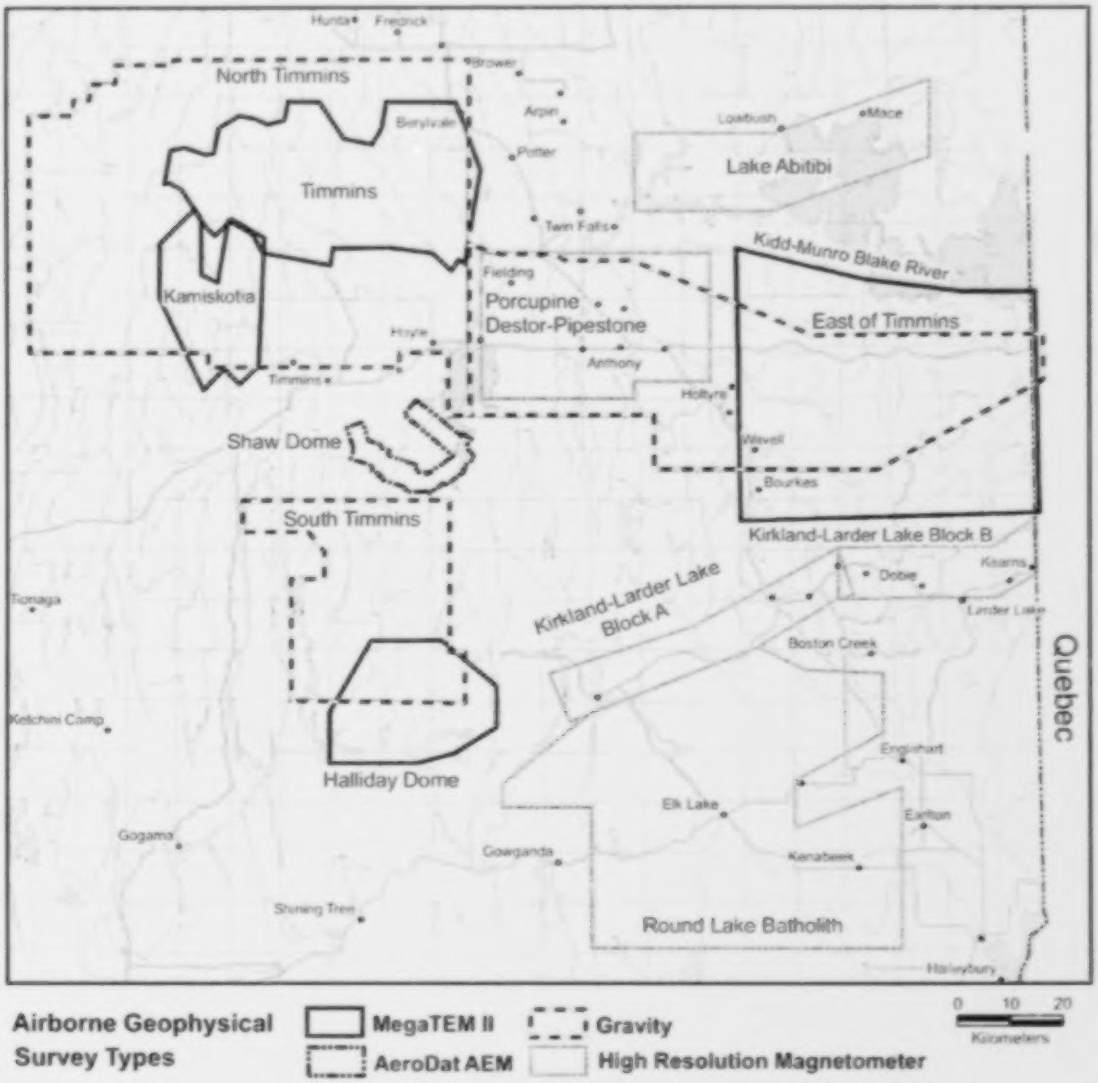

Hunta
Fredrick
Brower
North Timmins
Arpin
Berylvale
Potter
Timmins
Lowbush
Mace
Lake Abitibi
Twin Falls
Kidd-Munro Blake River
Fielding
Kamiskotia
Porcupine
Destor-Pipestone
East of Timmins
Hoyle
Anthony
Timmins
Holtyre
Shaw Dome
Wavell
Bourkes
South Timmins
Kirkland-Larder Lake Block B
Dobie
Kearns
Tionaga
Kirkland-Larder Lake
Block A
Larder Lake
Boston Creek
Quebec
Ketchini Camp
Englehart
Halliday Dome
Elk Lake
Earlton
Gogama
Gowganda
Kenabeek
Shining Tree
Round Lake Batholith
Haileybury
Airborne Geophysical
Survey Types
MegaTEM II
AeroDat AEM
Gravity
High Resolution Magnetometer
0
10
20
Kilometers

Figure 4.2. Discover Abitibi Initiative airborne geophysical survey areas.

High-resolution magnetometer surveys were completed over the Porcupine–Destor – Pipestone, Kirkland–Larder Lake, Lake Abitibi and the Round Lake Batholith areas. Low level, narrow line-spaced helicopter surveying was utilized in all areas except for the Round Lake survey.

Airborne gravity surveys were completed in several areas north, south and east of Timmins. Sander Geophysics donated an additional 2200 line kilometres of data to provide a seamless survey along the Porcupine–Destor deformation zone from west of Timmins to the Quebec border.

Data from the Ontario Treasure Hunt Spectrem 2000 TDEM survey flown in the Matheson area in 2000 (not shown on Figure 4.2), was reprocessed using new data processing technology in order to evaluate the airborne anomalies and, thus, to help further discriminate targets and improve the potential for new discoveries in this area.

The bedrock-mapping project (Architecture of the Abitibi Greenstone Belt) completed 9 subprojects from Kamiskotia to the Quebec border (*see* Figure 4.1 and "Greenstone Architecture Project" below for details). The subprojects provided new geological, stratigraphic, structural and metallogenic interpretations and three-dimensional geophysical inversions; investigated the relationship of gold mineralization to intrusions in the Timmins and Blake River areas; produced a regional metamorphic study to determine relationships between metamorphism and mineral deposits; as well as an in-kind OGS mapping project in the Shaw Dome area to better understand the relationship of Ni-Cu-(PGE) mineralization to komatiites.

The *Seismic* project completed nine lines of two-dimensional reflection seismic surveying using Vibroseis vehicles in the Timmins–Kirkland Lake area. Four lines, or parts of lines (total length of 153 km), were surveyed in a regional mode and 5 lines (total length of 51 km) were surveyed in a high resolution mode. The regional lines were oriented north-south to image the upper crust in the area from south of Timmins to Cochrane. The high-resolution lines were also oriented north-south and were focussed on the major gold-bearing structures of the prolific Porcupine–Destor and Larder Lake–Cadillac deformation zones. These data will provide another tool to investigate the upper crustal architecture of the AGB and the formation of the gold deposits along these faults.

The *Three Dimensional Modelling of Ore Deposits* project has produced models of 15 separate deposits that will give the user an overview of the 3D geology of the major gold and base metal deposits in the region. These data allow comparisons between the various deposits and will aid in exploration for new deposits of similar types.

A project utilizing three-dimensional modelling of overburden looked at the distribution and thickness of overburden north of Timmins to aid drift exploration surveys and help in the interpretation of geophysical anomalies. Exploration efforts will benefit from the increased understanding of drift thickness and distribution, including till units suitable for exploration and the effects of thick clay-rich sediments on geophysical surveys.

The *Geochemistry of Kimberlites* project provides a geochemical overview of known kimberlites, blind targets and non-kimberlite magnetic anomalies. Airborne magnetic survey anomalies may indicate the position of kimberlites or other economically important deposits. In areas of thick glacial drift cover, it may be difficult to determine the nature of these anomalies without expending substantial resources. A study to employ selective leach digestion of surface samples was completed to determine the effectiveness of this technique in defining selective leach geochemical signatures over known kimberlites, carbonatites, proven false anomalies and blind targets covered by thick glacial drift.

Results from 3 additional projects will be released as soon as possible. The Discover Abitibi Initiative is a unique project, which brought together all levels of government, industry and private sector individuals of like mind in pursuit of a common goal. Placing the management of the projects at the grassroots level and building the project from the bottom up has shown that this type of approach can succeed and that the benefits of the DAI will be felt for many years to come. The management and technical committees thank FedNor (Industry Canada), the Northern Ontario Heritage Fund Corporation and the private sector for financial and in-kind contributions and for the opportunity to bring this project to fruition.

THE GREENSTONE ARCHITECTURE PROJECT

The Greenstone Architecture Project was funded by the Discover Abitibi Initiative to provide a multidisciplinary approach to better understanding metallogeny in the Abitibi greenstone belt. Its objective was to improve knowledge of the stratigraphy, volcanology, geochemistry, metamorphic petrology, and structural geology of the greenstone belt, emphasizing selected mineralized and barren areas in order to better understand base metal and gold metallogeny and geological architecture in the Timmins and Kirkland Lake region.

A recently published overview report (Ayer, Thurston et al. 2005, and references therein) provides a regional perspective of the geological architecture and a synthesis of the results of the nine subprojects that constitute the Architecture project, each of which have their own publications. As such, it considerably advances understanding of Abitibi greenstone belt architecture and metallogeny with specific emphasis on Cu-Zn, Ni-Cu-PGE and gold mineralization and with numerous insights and recommendations that are directly applicable to exploration for these commodities.

We have considerably changed and improved our knowledge of Abitibi stratigraphy and belt-scale architecture utilizing 34 new thermal ionization mass spectrometry (TIMS) and 11 sensitive high-resolution ion microprobe (SHRIMP) U/Pb zircon ages to further subdivide and refine the distribution and age ranges for the volcanic and sedimentary assemblages, the intrusions and the timing of metallogenic and structural events. New xenocrystic evidence indicates that the Pacaud and Deloro assemblages were widespread basal units, but are now only found wrapped around the margins of external batholiths and in the cores of domes. A series of inter-formational unconformities in the volcanic "Keewatin" stratigraphic assemblages have been documented locally at the top of Pacaud, Deloro, Stoughton–Roquemaure and Kidd–Munro assemblages. The TIMS and SHRIMP data have also provided an improved understanding of the late sedimentary assemblages indicating that detritus for the Porcupine assemblage in the Timmins area was of local derivation with detrital zircon input peaking at about 2700–2690 Ma, coincident with the onset of D_1. Detritus for the Timiskaming assemblage sedimentary rocks were derived from both local Abitibi-age, and external pre-Abitibi sources indicating a more widespread provenance. The Timiskaming assemblage detrital zircon input peaked at 2690–2670 Ma, coincident with D_2 and D_3 folding and faulting.

The project has resulted in an improved understanding of the stratigraphy, facies associations and metallogeny at township scales within volcanogenic massive sulphide- (VMS) bearing assemblages in the Kamiskotia area by correlating the stratigraphy and the contained VMS mineralization to the upper Blake River assemblage, tracing mineralized stratigraphy from the Kam Kotia to the Jameland deposits (*see* Figure 4.1, BM-1), recognizing for the first time the alteration signatures of the various Kamiskotia deposits, and relating a number of the Kamiskotia VMS deposits to synvolcanic faults; in the Ben Nevis area, by developing stratigraphic and geochemical correlations with the uppermost part of the Blake River assemblage and comparisons with the Noranda and LaRonde camps, and documenting overprinting relations between VMS- and porphyry-style mineralization associated with the Clifford stock (*see* Figure

4.1, BM-2 and Int-1); in the Munro Township area, by documenting the regional setting of VMS mineralization in the Kidd–Munro assemblage at the Potter and Potterdoal deposits and erecting a stratigraphy in the central part of the assemblage in Munro Township (*see* Figure 4.1, BM-3), and by documenting lithologies, geochemical patterns and structural overprinting of the upper Tisdale and lower Blake River assemblages in Currie Township (*see* Figure 4.1, BM-4).

We have improved understanding of the stratigraphy, facies associations and metallogeny in the Shaw Dome area (*see* Figure 4.1, BM-5) by documenting the regional setting of Ni-Cu-PGE mineralization in the Tisdale assemblage, indicating the presence of important criteria for the generation of magmatic sulphide deposits including fertile komatiitic magma (metal source), proximity to sulphide iron formation (sulphur source), abundant olivine cumulate (heat source and dynamic system), and footwall embayments (physical traps).

The Timmins and Kirkland Lake–Larder Lake gold and intrusion subprojects utilized detailed mapping and structural studies, lithogeochemistry and geochronology to provide an improved understanding of the relationships between, and the ages of, the various assemblages, and the timing of intrusive, structural, alteration and epigenetic gold mineralization episodes (*see* Figure 4.1, Au-1, Au-2 and Int-2). The results of these studies documented the existence of multiple gold mineralizing events at both Timmins and Kirkland Lake.

In the Timmins area, the main structural and gold mineralization events included D_1 uplift and excision of upper Tisdale stratigraphy with formation of an angular unconformity pre-dating deposition of Porcupine assemblage at 2690 Ma. An early, lower grade gold mineralizing event predating the Timiskaming unconformity was probably synchronous with D_2 thrusting and folding and early south-over-north dip-slip movement on the Porcupine–Destor Deformation zone (PDDZ) between 2685 and 2676 Ma. Main stage gold mineralization was associated with a protracted D_3 event which coincided with the opening of the Timiskaming basin, but also overprinted the Timiskaming sediments. Rhenium-osmium geochronology on molybdenite associated with main-stage gold mineralization at the McIntyre Mine provide an age of 2672±7 Ma and 2670±10 Ma at the Dome Mine. D_4 included folding and faulting that preserved Timiskaming assemblages in synclines along the PDDZ and is associated with a late-stage gold mineralization event along the Pamour Mine trend.

In the Kirkland Lake–Larder Lake area, the main structural and gold mineralization events are post-Timiskaming and include a D_2 event corresponding with movement along the Larder Lake–Cadillac deformation zone and the deposits spatially associated with this deformation zone (possibly correlative with the D_3 event in Timmins). The D_3 event was related to the east-west shortening. The Kirkland Lake gold deposits are associated with the brittle to brittle-ductile Kirkland Lake fault (Main Break) and its subsidiary splays. The presence of open-space-filling textures in veins, and the association of veins with brittle faults suggest relatively shallow crustal levels of mineralization. Distinct metal signature and mineralization style suggest that the Kirkland Lake deposit probably represents a stand-alone hydrothermal system that is unrelated to gold deposits along the Larder Lake–Cadillac deformation zone and its splays. A deep magmatic fluid source appears most probable for the Kirkland Lake mineralization. Gold-bearing veins could have formed early in the D_4 event, synchronously with south-over-north reverse-dextral to reverse movement along the Main Break. Alternatively, mineralization could have predated D_4. Gold mineralization in the Narrows Break, north of the Kirkland Lake Main Break, was synchronous with northwest-southeast shortening during D_4.

A new metamorphic framework has provided additional constraints on the setting of gold deposits and a new tool for gold exploration. The metamorphic pattern in the Timmins to Kirkland lake region is the result of superposition of regional metamorphism on narrow higher grade contact metamorphic aureoles that formed at different times immediately adjacent to granitic intrusions, indicating that most of the granitoids are older than the regional metamorphic event. Pre-Timiskaming phases of deformation were less penetrative and occurred at shallower depths in the crust and at lower temperatures than post-Timiskaming deformation, whereas post-Timiskaming deformation, when peak regional metamorphic conditions prevailed, was most conducive to formation of large syn-metamorphic (orogenic) gold deposits. There is a striking spatial relationship of the boundary between the lower and upper greenschist metamorphic zones and a significant number of gold mines. Newly identified high priority targets are defined by the coincidence of metamorphic anomalies with major structural features, specific rock compositions, and moderate to intense deformation.

Regional structural patterns are now better understood, in part based upon improved knowledge of the distribution of the stratigraphy and intrusions in conjunction with detailed and regional scale geophysical surveys including magnetic, gravity and reflection seismic surveys. Major external intrusive units such as Round Lake and Kenogamissi batholiths include synvolcanic phases that occupy anticlinal culminations, whereas the later syntectonic intrusions had a relatively minor localized structural effect on the surrounding supracrustal rocks. Regional deformation zones are the loci of major faults which have been reactivated repeatedly and have exerted control on the distribution of early volcanic ("Keewatin") and late sedimentary assemblages. All assemblages were constructed in an autochthonous fashion and have been locally juxtaposed along regional structures during major ductile deformation events that involved predominantly north-south transpressional shortening. Our geophysical inversions of magnetic and gravity data have demonstrated the sense of dip on a number of major structures and lithological units.

CONCLUSIONS

In summary, many exciting new advances in our understanding of the geology of the Abitibi greenstone belt are being made. The reports in this volume demonstrate the merits of a diverse, but balanced, approach to Abitibi area geology using the traditional strengths of Precambrian Geoscience Section bedrock mapping, the comprehensive understanding of the ore deposits by the mining companies working in the area and the research skills of university geology departments. The Discover Abitibi Initiative has provided a unique opportunity to fund new, innovative, mapping-based research on key metallogenic problems in the Abitibi greenstone belt using Federal, Provincial and Industry funding and in-kind support from the OGS. This balanced approach to mapping and research embraces projects at a wide variety of scales and methodologies that are required for the range of problems that exist. The projects range from belt-wide compilation, to township-scale bedrock mapping to extremely detailed outcrop-scale mapping. The program is also focussed on the economically important parts of the belt. We feel our integrated approach to applied research through collaboration with our mining company clients and the earth science departments of a number of universities is needed to advance our understanding of the geology and its relationship to mineral deposits in this geologically complex, but highly prospective, part of the province. We also feel confident that the maps, reports and theses resulting from this comprehensive program will provide many new ideas and concepts that are, and that will continue to be, directly applicable to exploration for new mineral deposits.

REFERENCES

Ayer, J., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K. and Trowell, N. 2002. Evolution of the southern Abitibi greenstone belt based on U-Pb geochronology: autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation; Precambrian Research, v.115, p.63-95.

Ayer, J.A., Berger, B.R., Hall, L.A.F., Houlé, M.G., Johns, G.W., Josey, S., Madon, Z., Rainsford, D. and Trowell, N.F. 2005. Geological compilation of the central Abitibi greenstone belt: Kapuskasing Structural Zone to the Québec border; Ontario Geological Survey, Preliminary Map P.3565, scale 1:250 000.

Ayer, J.A., Thurston, P.C., Bateman, R., Dubé, B., Gibson, H.L., Hamilton, M.A., Hathway, B., Hocker, S.M., Houlé, M.G., Hudac, G., Ispolatov, V.O., Lafrance, B., Lesher, C.M., MacDonald, P.J., Péloquin, A.S., Piercey, S.J., Reed, L.E. and Thompson, P.H. 2005. Overview of results of the Greenstone Architecture Project: Discover Abitibi Initiative; Ontario Geological Survey, Open File Report 6154, 146p.

Ayer, J.A., Trowell, N.F. and Josey, S. 2004. Geological compilation of the Abitibi greenstone belt; Ontario Geological Survey, Miscellaneous Release—Data 143.

Berger, B.R. 2004. Geology of Burt–Holmes area, District of Timiskaming; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.5-1 to 5-9.

Houlé, M.G. and Guilmette, C. 2004. Geology and mineral potential of Carman and Langmuir townships; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.7-1 to 7-16.

Vaillancourt, C., Ayer, J.A., Zubowski, S.M. and Kamo, S.L. 2004. Synthesis and timing of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt: Menzies and Musquash townships; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.6-1 to 6-9.

5. Project Unit 05-004. General Geology of Powell Township, District of Timiskaming

B.R. Berger[1] **and S. Préfontaine**[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Powell Township along with Bannockburn and Montrose townships (*see* Préfontaine and Berger, this volume) were mapped at 1:20 000 scale to better define the stratigraphy, the structural features and mineralization in this part of the Abitibi greenstone belt west of Kirkland Lake (Figure 5.1). Previous mapping by Dyer (1936), Lovell (1967) and Jensen (1995) defined the major rock types and important structures; however, recent nickel-copper discoveries in Bannockburn Township by Mustang Minerals Corporation and continuing gold exploration in Powell Township provided the impetus to re-examine the area.

GENERAL GEOLOGY

Neoarchean ultramafic, mafic and intermediate metavolcanic rocks and clastic metasedimentary rocks underlie Powell Township (Figure 5.2). Neoarchean alkalic intrusions, composed of syenite, feldspar porphyry, mafic syenite, and lamprophyre, intrude the supracrustal rocks and are spatially related to copper-molybdenum mineralization in the Ryan Lake area and gold mineralization throughout the map area.

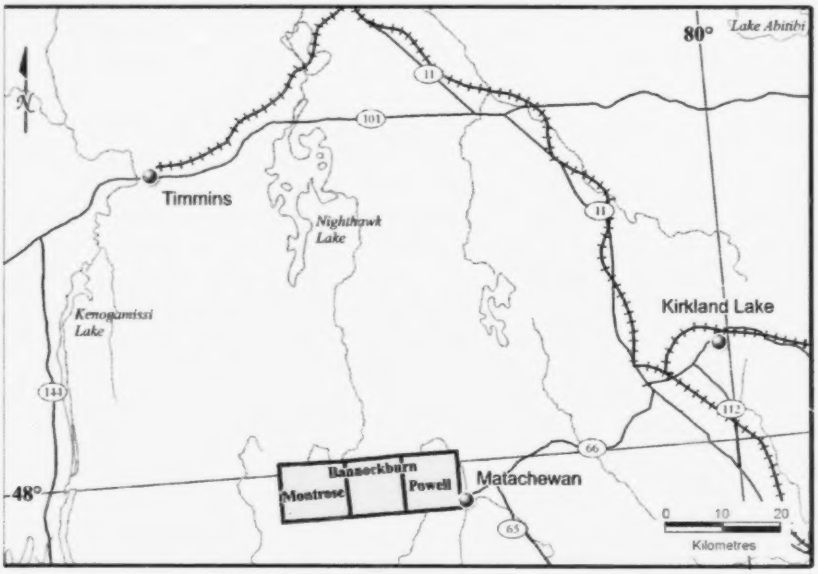

80°
Lake Abitibi
N
11
101
Timmins
Nighthawk Lake
11
Kirkland Lake
Kenogamissi Lake
144
112
66
Bannockburn
Montrose
Powell
Matachewan
48°
65
0
10
20
Kilometres

Figure 5.1. General location map for this study.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.5-1 to 5-10.

© *Queen's Printer for Ontario, 2005*

Clastic metasedimentary rocks, composed of conglomerate, sandstone, wacke and argillite, unconformably overlie the Neoarchean rocks in the southern part of Powell Township and are correlated with the Gowganda Formation of the Cobalt Group of the Huronian Supergroup (Lovell 1967; Dyer 1936).

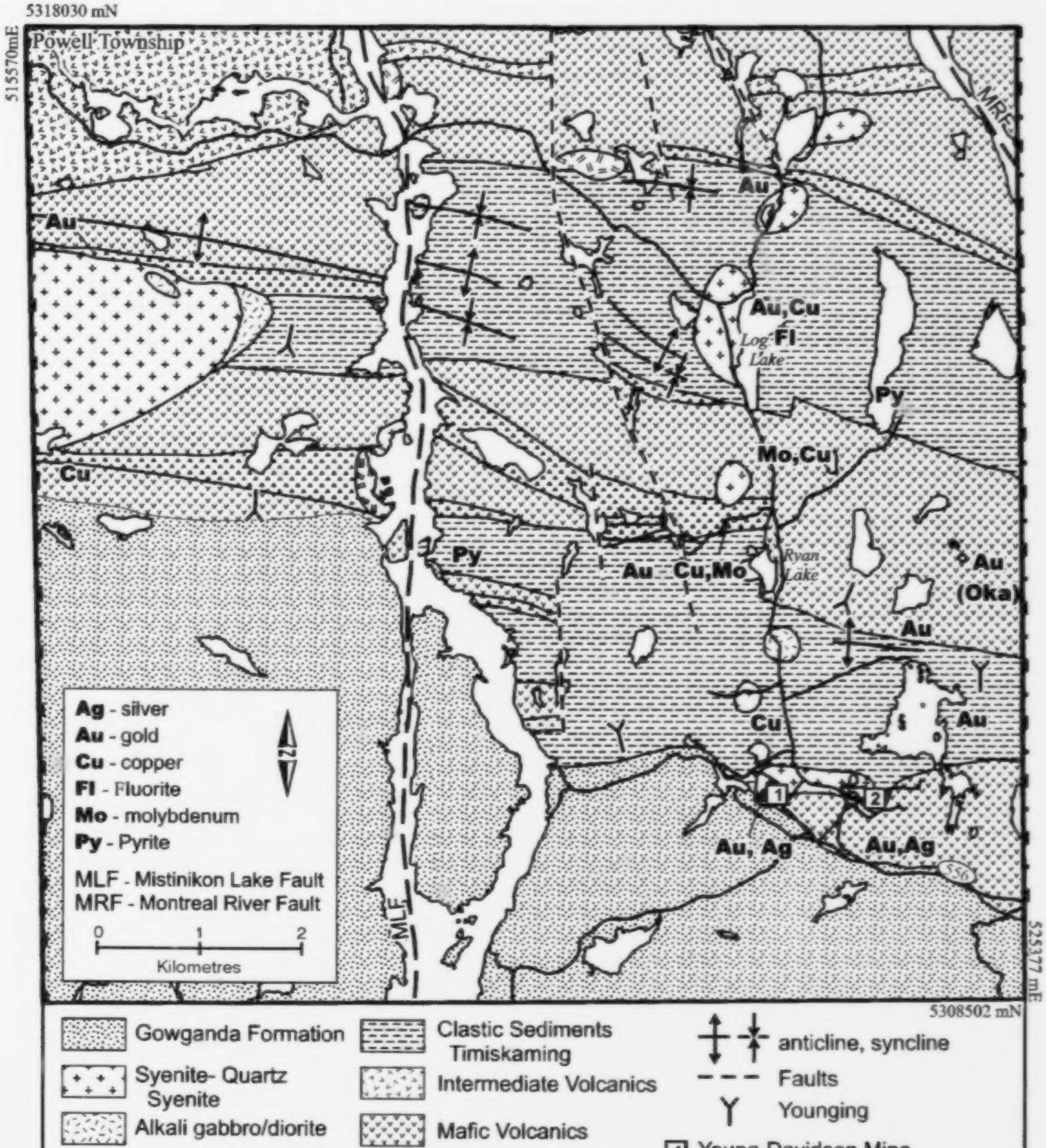

5318030 mN
515570mE
Powell Township
MRF
Au
Au
Au,Cu
Fl
Log Lake
Py
Mo,Cu
Cu
Py
Au
Cu,Mo
Ryan Lake
Au
(Oka)
Au
Cu
Au
1
2
Au, Ag
Au,Ag
556
MLF
525377 mE
5308502 mN
Ag - silver
Au - gold
Cu - copper
Fl - Fluorite
Mo - molybdenum
Py - Pyrite
N
MLF - Mistinikon Lake Fault
MRF - Montreal River Fault
0
1
2
Kilometres
Gowganda Formation
Syenite- Quartz Syenite
Alkali gabbro/diorite
Peridotite/gabbro
Clastic Sediments Timiskaming
Intermediate Volcanics
Mafic Volcanics
Ultramafic volcanics
anticline, syncline
Faults
Younging
1 Young-Davidson Mine
2 Consolidated Matachewan Mine

Figure 5.2. General geology of Powell Township.

Diabase dikes correlated with the Matachewan dike swarm intruded the Neoarchean rocks and are most common between the Montreal River fault in Cairo Township and the Mistinikon Lake fault (*see* Figure 5.2; Berger and Leblanc 2002; Lovell 1967). Sill-like diabase intrusions cluster at the unconformity between the Neoarchean rocks and the Gowganda Formation and may belong to the Nipissing diabase swarm. Lovell (1967) indicated dikes of Nipissing diabase cut the Gowganda Formation in the east part of Powell Township.

Neoarchean and Proterozoic deformation has resulted in a complex pattern of folding, shearing and faulting.

Neoarchean

Ultramafic metavolcanic rocks (komatiite) occur throughout Powell Township and their abundance was underestimated by previous mapping. Several units occur east of the Mistinikon Lake fault and are composed of dark green to black weathering massive cumulate-textured peridotite, pyroxene and rare olivine spinifex-textured flows, abundant flow breccia and schist. Komatiite is usually intercalated with mafic metavolcanic rocks, but is in contact with clastic metasedimentary rocks in several places. Carbonate and green mica alteration is common along the komatiite-sedimentary rock contact and may be accompanied by gold mineralization. Regional airborne geophysical magnetic data (OGS 2004, 2003) can be used to trace the ultramafic rocks and is most useful where they are covered by overburden. However, ultramafic rocks with low magnetic susceptibility were encountered in the field and recognition of such rocks may not be possible using airborne magnetic geophysical data.

Only two ultramafic metavolcanic units were located west of the Mistinikon Lake fault. A unit of massive cumulate-textured peridotite occurs at the unconformity with the Gowganda Formation and can be traced westward to the contact of a syenite intrusion. Another unit of schistose, spinifex and flow brecciated komatiites occurs along the north contact of Neoarchean clastic metasedimentary rocks and was traced along the north contact of the large syenite intrusion into Bannockburn Township where the unit appears to pinch out.

Mafic metavolcanic rocks are dark green, green and light green weathering and are most commonly composed of massive, pillowed or pillow brecciated flows. These rocks occur in three separate bands and underlie the north, central and south parts of the township (*see* Figure 5.2). The north unit is strongly recrystallized and, in many places, massive flows are diabase textured and epidote altered. Intermediate pyroclastic and epiclastic rocks are intercalated with the mafic units and komatiitic metavolcanic rocks occur along the south boundary with clastic metasedimentary rocks. The unit extends west of the Mistinikon Lake fault where rocks are mainly pillowed and continues into Bannockburn Township (*see* Préfontaine and Berger, this volume).

The central band of mafic metavolcanic rocks is composed mostly of pillowed flows with subordinate massive flows and schist. The unit is mixed with komatiite flows and intrusive peridotite and locally contains tectonic slivers of clastic metasedimentary rocks to the east. Map pattern, stratigraphic facings of the pillows and komatiites and airborne magnetic geophysical data (OGS 2003, 2004) indicate that the unit is complexly folded around west-northwest-striking fold axes. The central band is poorly exposed west of the Mistinikon Lake fault, but appears to extend west where it is in contact with a syenite intrusion and is unconformably overlain by the Gowganda Formation.

The band of mafic metavolcanic rocks in southern Powell Township is composed of massive, pillowed and schistose flows. Development of intense pressure-solution cleavage creates the impression that the schistose rocks are sediments. However, the lack of relict clastic grains, grain gradation, loading or any other primary sedimentary features indicates that the banding in the rocks results from deformation. The mafic metavolcanic rocks are intensely altered by addition of carbonate, hematite and magnetite near the Young–Davidson and Consolidated Matachewan mines. Calcite-magnetite alteration along the boundary between Cairo and Powell townships is attributed by the authors to prograde metamorphism of an earlier iron carbonate alteration similar to that described by Chorlton (1988) near the Goldlund Mine south of Sioux Lookout. The south band of metavolcanic rocks displays interference folds patterns and sinistral displacement along southwest-striking shear planes. Numerous syenite intrusions occur throughout the mafic metavolcanic rocks and the largest one is host to the Young–Davidson gold deposit and part of the Consolidated Matachewan gold deposit. The south band of mafic metavolcanic rocks is terminated at the unconformity with the Gowganda Formation.

Intermediate metavolcanic rocks are composed predominantly of epiclastic and pyroclastic deposits with minor flows. Intermediate rocks that underlie northwest Powell Township contain amphibole and plagioclase phenocrysts and are contiguous with intermediate metavolcanic rocks described by Kresz (1993) in Baden and Argyle townships and in Bannockburn described by Préfontaine and Berger (this volume). Lapilli tuff is most common with andesitic clasts varying from 2 to 40 mm in size with the rare fragment to 60 mm. Lapilli tuff deposits are generally massive and display neither bedding nor clast gradation. Tuff breccia deposits are similar to lapilli tuff except maximum clast size is up to 30 cm. Andesitic to dacitic tuff and tuff breccia is intercalated with mafic metavolcanic rocks in north Powell Township east of the Mistinikon Lake fault. These rocks are white to light grey weathering, feldspar and rarely quartz phyric and do not appear to be similar to intermediate rocks previously described.

Clastic and chemical metasedimentary rocks are composed of conglomerate, wacke, siltstone, argillite, chert and rare pyrite-magnetite iron formation. Two bands of metasedimentary rocks were mapped east of the of the Mistinikon Lake fault. The northern band (*see* Figure 5.2) is composed mostly of thickly bedded to laminated wacke, siltstone, argillite and chert. Rare alkalic tuff is interbedded with the metasedimentary rocks and numerous alkalic dikes and small plutons are intruded into the sequence. The northern band consists of turbidites with AE and rarely C divisions of the Bouma cycle (cf. Walker 1992). Uranium-lead zircon geochronology indicates that these rocks are less than 2686 Ma and represent the lower part of the Timiskaming assemblage in this part of the Abitibi greenstone belt (Ayer et al. 2002). Several west-northwest-striking fold axes are defined by reversals in stratigraphic facings, which indicate that the north band of metasedimentary rocks is tectonically thickened and structurally complex east of Mistinikon Lake fault. The northern band of metasedimentary rocks extends west of the Mistinikon Lake fault and primary features such as grain gradation, small-scale cross-bedding and load casts are commonly well preserved as ACE turbidites. The band extends west to the contact with a syenite intrusion and becomes intercalated with ultramafic flows along the north side of the intrusion.

The southern band of metasedimentary rocks is restricted to the east side of the Mistinikon Lake fault and is composed of conglomerate, wacke, arkose, argillite and rare pyritic chert. The conglomerate is clast to matrix supported with rounded to subangular clasts of mostly felsic metavolcanic rocks and chert up to 30 cm in size. Rare green mica and mafic metavolcanic clasts were observed locally. The conglomerate is poorly sorted, poorly bedded and massive. Massive arkose and wacke are interbedded with the conglomerate and, in many places, small pebbles are up to 3 cm. Rare trough cross-beds, ripples and low-angle cross-stratification were observed in the sandy beds and this is interpreted to indicate deposition in a fluvial environment. The conglomerate and associated wacke, arkose and argillite are correlated with the Timiskaming assemblage by the authors. Stratigraphic facings are poorly preserved in the southern band of metasedimentary rocks; however, facing reversals were observed near the contacts with the southern and central bands of metavolcanic rocks.

Ultramafic and mafic intrusive rocks are associated with the komatiitic flows in two places in Powell Township. Massive peridotite and gabbro form a small intrusion in north-central Powell Township near the contact between the northern band of mafic metavolcanic rocks and clastic metasedimentary rocks. These intrusive rocks may represent a small subvolcanic sill or magma chamber associated with the komatiitic volcanism. Another small peridotite intrusion is located on the western shore of Mistinikon Lake and also possibly represents a subvolcanic magma chamber for the komatiitic volcanism.

Alkaline intrusions vary in composition from hornblendite, alkalic gabbro, lamprophyre, monzonite, syenite and alkaline granite and occur throughout Powell Township as dikes, sills and small to large plutons. Hornblendite occurs only locally as dikes in the clastic metasedimentary rocks and as minor units, which are too small to be shown at 1:20 000 scale, within the large alkalic pluton in the western part of the township. Alkali gabbro is recognized in the field by the presence of biotite and pink feldspar and occurs as small dikes and as a discontinuous border phase of the large alkalic pluton (*see* Figure 5.2). Biotite-bearing lamprophyre occurs as dikes throughout the map area, but is concentrated near the Consolidated Matachewan gold mine in southeast Powell Township. Several dikes in this area contain abundant greenstone and metasedimentary xenoliths that serve to distinguish the lamprophyre from other mafic alkalic dikes.

Many textural varieties of syenite occur in the map area. Massive, medium-grained equigranular syenite to syenodiorite with 25 to 40% amphibole and biotite is most common. Most of the large pluton is composed of this type of syenite as are portions of the intrusions in southern and northern Powell Township. Portions of the alkalic intrusion hosting the Young–Davidson gold deposit are also massive and equigranular. Potassium feldspar porphyritic syenite is common and occurs as red and grey phases of dikes and plutons in the central part of the township. This type of syenite is most common in the Ryan Lake area where copper and molybdenum mineralization occurs. Alkaline granite is pink, equigranular and contains up to 20% quartz. This type of rock occurs only in the core of the pluton in west Powell Township.

Paleoproterozoic

Several mafic dikes composed of diabase and quartz diabase intruded the Neoarchean rocks. These dikes mostly occur east of the Mistinikon Lake fault and are correlated with the Matachewan swarm by the authors (cf. Lovell 1967; Osmani 1991). The dikes vary from a few centimetres to over 75 m wide and may be either equigranular or feldspar porphyritic with individual plagioclase crystals to 5 cm in size. The diabase has variable magnetic susceptibility with ranges up to 2 orders of magnitude common across and along individual dikes. This attribute was not observed in dikes east of the map area (Berger and Leblanc 2002; Pigeon and Berger 2003), which indicates the unusual nature of the rocks in Powell Township (see below).

Diabase clusters adjacent to the unconformity between the Neoarchean rocks and the Paleoproterozoic Gowganda Formation near the Young–Davidson gold deposit (*see* Figure 5.2). Much of this diabase occurs as dikes similar to those described above. Some diabase, although texturally similar to dikes occurs as sills parallel to the unconformity. This feature combined with quartz-calcite veining and pressure-solution cleavage in the Gowganda Formation conglomerate at the unconformity suggests that the sills may belong to the Nipissing diabase swarm (cf. Osmani 1991).

The Gowganda Formation of the Cobalt Group of the Huronian Supergroup is composed of clastic metasedimentary rocks. Matrix- and rare clast-supported conglomerate is the most abundant rock type with granitoid, greenstone, metasedimentary and rare gneissic clasts. Wacke, sandstone and argillite beds varying from less than 1 to 30 cm thick are commonly interbedded with the conglomerate. Wacke and sandstone contain medium to very coarse sand and are commonly grey, ungraded rocks that contain abundant feldspar and quartz with locally abundant lithic fragments and pebbles. Red sandstone is a distinctive rock type that occurs as continuous and discontinuous beds throughout the Gowganda Formation, but is more abundant west of the Mistinikon Lake fault where it is interbedded with argillite.

STRUCTURE AND METAMORPHISM

The rocks in Powell Township are complexly deformed with evidence for Neoarchean and Proterozoic deformation. The Mistinikon Lake fault divides the Neoarchean rocks into 2 structural domains and the Gowganda Formation represents a third domain (*see* Figure 5.2).

West of the Mistinikon Lake fault, the Neoarchean rocks display a weak to moderate west-northwest-striking S_1 foliation that is generally parallel to stratigraphy. Reversals of pillowed flow tops and spinifex-textured komatiitic flows define a westerly striking anticline axis north of the alkalic intrusion in this part of the map area. A weakly developed west-southwest S_2 crenulation foliation is observed locally. A southwest-striking iron carbonate and sericite schist unit within the intermediate metavolcanic rocks in northwest Powell Township is interpreted to be a S_2 deformation zone. Very rarely, a third generation of north to north-northeast spaced foliation affects the rocks and is locally coincident with late brittle faults.

Neoarchean rocks between the Mistinikon Lake and Montreal River faults are strongly deformed with evidence for multiple folding, shearing and faulting (*see* Figure 5.2). A moderate to strongly developed north-northwest-striking S_1 foliation is developed parallel to lithological contacts and is axial planar to several F_1 fold axes throughout this part of the map area (*see* Figure 5.2). The S_1 foliation occurs as an intense pressure-solution cleavage in mafic metavolcanic rocks south of the Consolidated Matachewan gold mine and the resultant banding resembles sedimentary bedding.

S_1 and F_1 are overprinted by a southwest-striking S_2 foliation that is axial planar to a second generation of upright F_2 folds that plunge moderately to the southwest. This creates a very complex interference fold pattern especially in the vicinity of the Consolidated Matachewan and Young–Davidson gold mines. The F_2 folds are modified by sinistral shearing along S_2 planes that have resulted in transposition of folds and stratigraphy (Photo 5.1). Second generation extension and L_2 mineral lineations are parallel to the plunge of the F_2 folds and locally control gold mineralization in the south part of the township.

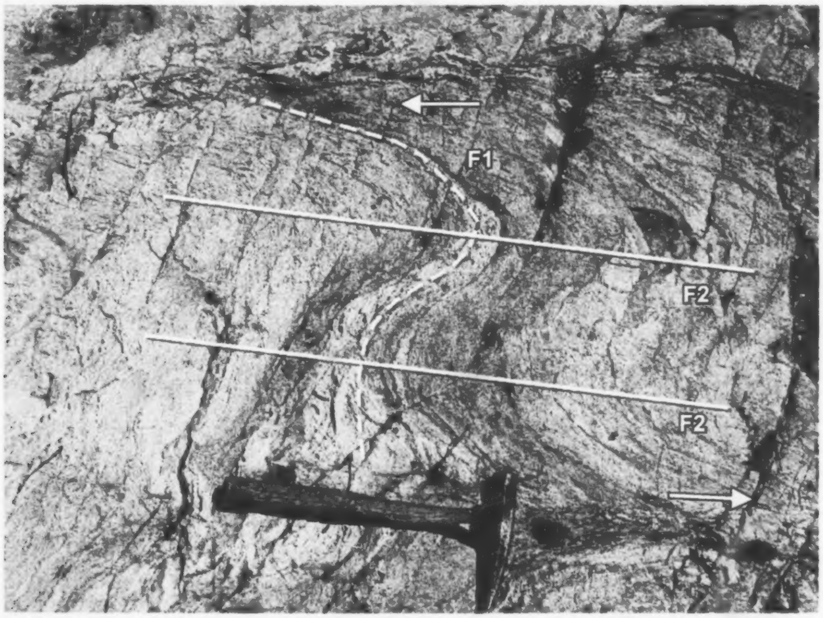


Photo 5.1. Interference fold pattern modified by sinistral shearing. Stripped outcrop, Consolidated Matachewan gold mine property, UTM location: NAD83, Zone 17, 524600E, 5310367N.

A third foliation oriented between 170 and 210° was observed in several outcrops east of the Mistinikon Lake fault. The foliation most commonly occurs as a set of spaced fractures, but locally occurs as a penetrative foliation especially in the northern band of metasedimentary rocks (see above) and along the eastern boundary of the map area. The foliation is coincident with several brittle faults and extends into the Gowganda Formation at the unconformity with the Neoarchean rocks. Powell and Hodgson (1992) inferred that Proterozoic deformation was entirely responsible for the formation of this foliation; however, the development of north-striking shear zones coupled with the penetrative nature of the foliation lead the authors to believe that the foliation was initially developed in the Neoarchean and subsequently reactivated during the Proterozoic.

The main part of the Cadillac–Larder Lake deformation zone (CLDZ) occurs in the south part of Cairo Township immediately east of the map area and extends up to the Montreal River fault at Matachewan (Berger and Leblanc 2002). Schistose mafic metavolcanic rocks along Highway 566 may represent the CLDZ in southeast Powell Township; however, these rocks are intensely folded and display no sense of shearing. The CLDZ east of the map area consistently displays dextral kinematic indicators between Matachewan and Kenogami (Berger and Leblanc 2002; Pigeon and Berger 2003; Berger 2004). The authors cannot explain this apparent contradiction at this time and it may be that the CLDZ does not occur in Powell Township; alternatively the deformation zone may underlie the Gowganda Formation in Yarrow Township to the south.

The Paleoproterozoic Gowganda Formation displays disharmonic open folding and flexure and represents the third structural domain in the map area (cf. Lovell 1967). Locally, north-striking pressure-solution cleavage, quartz and calcite veining were observed, especially near the unconformity with the Neoarchean rocks. This indicates that the unconformity was a pathway for hydrothermal fluids in the map area. Powell and Hodgson (1992) indicated that Proterozoic deformation resulted in reactivation of Archean structures and the foliation in the overlying Gowganda Formation. The Mistinikon Lake and Montreal River faults are examples of reactivated Archean structures. Foliated zones in the Gowganda Formation can be used to locate hidden Archean structures and may provide additional evidence for concealed mineralization.

Neoarchean rocks west of the Mistinikon Lake fault are metamorphosed to the greenschist facies with chlorite, epidote and secondary amphibole most common in the mafic metavolcanic rocks. Chlorite, white mica and rarely epidote are observed in the intermediate metavolcanic and clastic metasedimentary rocks. Hornblende, magnetite and abundant epidote are developed adjacent to the alkalic intrusion and indicate higher temperatures affected the rocks in this area.

Neoarchean rocks east of the Mistinikon Lake fault are metamorphosed to upper greenschist and locally amphibolite facies. Mafic metavolcanic rocks in the northern part of the township are recrystallized and locally are gabbroic textured with abundant secondary amphibole, epidote and chlorite. White porphyroblasts in the clastic metasedimentary rocks are inferred to be retrograded cordierite based on crystal habit, but may also be staurolite and indicate high temperature metamorphism. Much of the southeastern part of Powell Township is affected by hydrothermal alteration related to gold mineralization. Iron carbonate, sericite (green mica), quartz and hematite are most abundant. Iron carbonate is locally metamorphosed to calcite and magnetite along the north-striking shear zone at the east boundary of the map area and this indicates high temperature metamorphism of the previous alteration (cf. Chorlton 1988).

The Gowganda Formation appears to be weakly metamorphosed; however, feldspar and epidote veining was observed in a few locations, which suggests greenschist-grade metamorphic conditions were attained locally.

MINERALIZATION

The discovery of gold in southeast Powell Township in 1916 resulted in the development of the Young–Davidson and Consolidated Matachewan mines that, combined, produced 957 000 ounces gold and 266 000 ounces silver (cf. Lovell 1967). Ryan Lake Mines Limited produced near 5 000 000 pounds of copper, 36 000 ounces silver, 1300 ounces gold and an undisclosed amount of molybdenum from a deposit north of Ryan Lake in the centre of Powell Township (Lovell 1967). Continued exploration throughout the township resulted in additional discoveries of gold, copper and molybdenum mineralization. The present mapping indicates that there are three major environments that host the bulk of the mineralization.

The first mineralized environment is associated with alkalic intrusions. Figure 5.2 shows that the past-producing mines are hosted in syenitic intrusions that are aligned along a north-striking trend in the central part of Powell Township. This string of intrusions displays a crude textural and mineral zonation that suggests they are all co-genetic. Potassium feldspar porphyritic syenite is most common in the central intrusions that host copper, molybdenum, fluorite and lesser amounts of gold and silver. Equigranular syenite is more commonly mixed with porphyritic syenite in the most northern and most southern intrusions that host gold and silver. Similarly, hydrothermal alteration shows a distinct zonation with hematite, sericite, potassium feldspar and weak silicification more common in the central intrusions. Iron carbonate, sericite, erratic hematization, and strong silicification are more common in the north and south. Many mafic and felsic alkalic dikes accompanied by pyrite and silification intrude the Neoarchean supracrustal rocks east of the Mistinikon Lake fault, but the dikes tend to be more common in the vicinity of the north-trending string of intrusions in central Powell and this suggests the dikes are related to the intrusions. The Young–Davidson and Consolidated Matachewan gold deposits display a strong association with syenite, but the mineralization also shows that many ore zones are structurally controlled by the L_2 lineation (see above).

The second mineralized environment occurs along the contact between komatiitic flows and the clastic metasedimentary rocks. Numerous gold showings occur at or near this contact throughout the township and many similarities were noted. At many of the showings, the komatiite–metasedimentary contact is abrupt and commonly contains abundant pyrite with lesser amounts of base metals. Many contacts display locally intense deformation with strong iron carbonate and weak green mica alteration. Gold mineralization is erratic, but locally high grade and may be associated with structural features oblique to the strike of the contact.

The third mineralized environment is represented by a single gold occurrence in the east central part of the township (Oka: *see* Figure 5.2). At this occurrence, gold is associated with komatiitic and mafic metavolcanic flows in sheared contact with clastic metasedimentary rocks and recrystallized pyrite-magnetite iron formation. The Oka occurrence is contained within the centre band of metavolcanic rocks and shows a stronger structural control than gold occurrences along the komatiite–metasedimentary contact. Low grade gold is widespread and hydrothermal alteration is not as strongly developed as in other areas.

SUMMARY AND RECOMMENDATIONS

All field evidence indicates that the panel of Neoarchean rocks between the Mistinikon Lake and Montreal River faults is structurally and metamorphically unique in this part of the Abitibi greenstone belt. The supracrustal rocks are complexly folded and affected by shearing that is not evident east or west of the panel (Préfontaine and Berger, this volume; Berger and Leblanc 2002). Extensive recrystallization in mafic metavolcanic rocks and cordierite porphyroblasts in clastic metasedimentary rocks indicate regional metamorphism attained upper greenschist grade, whereas Neoarchean rocks north and west of the map area are much lower grade (Powell and Hodgson 1992; Kresz 1993). Diabase dikes of the Matachewan swarm within the panel display greater variability in magnetic susceptibility than dikes east of the map area (Berger and Leblanc 2002; Pigeon and Berger 2003). There is a greater number of mineral occurrences within the panel than either to the west or east. The authors interpret the central panel to be a significantly uplifted block that exposes a deeper crustal level than the areas to the east or west. The central panel has experienced significantly high fluid flow as evidenced by the abundance of pressure-solution cleavage and widespread hydrothermal alteration. High fluid flow would promote strain softening of the rocks during deformation and increase permeability resulting in increased mineralization.

The string of north-trending alkalic intrusions is an attractive exploration target both for precious and base metals. Specifically, the area north of the Ryan Lake Mine to Highway 566 should be explored for copper, molybdenum and gold. The most northern intrusion has not been extensively explored and should be a suitable host for gold mineralization. The intrusion west of Log Lake (*see* Figure 5.2) is another favourable target for gold and copper.

The komatiite–metasedimentary rocks contact is a prospective zone for gold. Several showings at or near this contact indicate the entire strike length throughout Powell Township should be examined. Widespread iron carbonate alteration on Mistinikon Lake and some of the higher grade gold occurrences indicate that the most northern contact may be a more prospective area than others.

The Oka gold occurrence is a relatively new discovery and the full potential for similar gold mineralization is not known. However, further exploration west of Oka may prove to be successful.

REFERENCES

Ayer, J., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K. and Trowell, N. 2002. Evolution of the southern Abitibi greenstone belt based on U–Pb geochronology: autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation; Precambrian Research, v.115, p.63-95.

Berger, B.R. 2004. Geology of Burt–Holmes area, District of Timiskaming; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.5-1 to 5-9.

Berger, B.R. and Leblanc, G. 2002. Geology of Cairo Township, District of Timiskaming; *in* Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.8-1 to 8-7.

Chorlton, L. 1988. Geological synopsis in the Dinorwic–Sioux Lookout area – the Sandybeach Lake area, northwestern Ontario; *in* Summary of Field Work and Other Activities 1988, Ontario Geological Survey, Miscellaneous Paper 141, p.153-162.

Dyer, W.S. 1936. Geology and ore deposits of the Matachewan–Kenogami area; Ontario Department of Mines, Annual Report, 1935, v.44, pt.2, p.1-55.

Jensen, L.S. 1995. Precambrian geology, Powell Township; Ontario Geological Survey, Preliminary Map P.3356, scale 1:20 000.

Kresz, D.U. 1993. Geology of Argyle and Baden townships; Ontario Geological Survey, Open File Report 5874, 114p.

Lovell, H.L. 1967. Geology of the Matachewan area; Ontario Department of Mines, Geological Report 51, 61p. Accompanied by coloured maps 2109, 2110, scale 1:31 680.

Ontario Geological Survey 2003. Ontario airborne geophysical surveys, magnetic and electromagnetic data, grid and vector data and profile data, Kirkland Lake area; Ontario Geological Survey, Geophysical Data Set 1102–Revised.

——— 2004. Ontario airborne geophysical surveys, magnetic data, grid and vector data and profile data, Kirkland Lake–Larder Lake area; Ontario Geological Survey, Geophysical Data Set 1053.

Osmani, I.A. 1991. Proterozoic mafic dike swarms in the Superior Province of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.661-681.

Pigeon, L. and Berger, B.R. 2003. Geology of Eby and Otto townships, District of Timiskaming; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.7-1 to 7-8.

——— 2004. Precambrian geology, Otto and Eby townships; Ontario Geological Survey, Preliminary Map P.3534, scale 1:20 000.

Powell, W.G. and Hodgson, C.J. 1992. Deformation of the Gowganda Formation, Matachewan area, Ontario, by post-Early Proterozoic reactivation of the Archean Larder Lake–Cadillac break, with implications for gold exploration; Canadian Journal of Earth Sciences, v.29, p.1580-1589.

Walker, R.G. 1992. Turbidites and submarine fans; *in* Facies models: response to sea level change, Geological Association of Canada, GEOtext 1, p.239-264.

6. Project Unit 05-004. Geology of Bannockburn and Montrose Townships, District of Timiskaming

S. Préfontaine[1] and B.R. Berger[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Montrose Township and part of Bannockburn Township were mapped at a scale of 1:20 000 this summer (approximately 170 km^2; Figure 6.1). Both of these townships were previously mapped by Cooke (1919) and incorporated in a compilation map of the area done by Rickaby (1932). More recently, they were mapped by L.S. Jensen (1996). Hence, the townships were remapped to improve the quality and the quantity of the geological database for this area.

GENERAL GEOLOGY

Montrose and Bannockburn townships are part of the Abitibi greenstone belt in the Superior Province. Neoarchean and Proterozoic rocks underlie the map area. The older rocks are composed of ultramafic, mafic, intermediate and felsic metavolcanic rocks and related intrusive as well as felsic volcaniclastic metasedimentary rocks. Quartz diorite and syenite intrude these rocks in Bannockburn Township. Gabbro and gabbroic textured rocks are found in both townships (Figure 6.2).

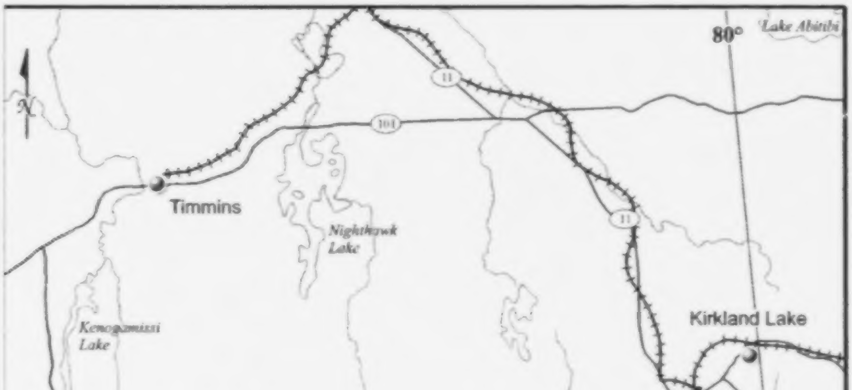

N
80°
Lake Abitibi
11
101
Timmins
Nighthawk Lake
11
Kenogamissi Lake
Kirkland Lake
144
112
66
Bannockburn
Montrose
Powell
Matachewan
48°
65
0
10
20
Kilometres

Figure 6.1. General location map for this study.

Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, p.6-1 to 6-7

© Queen's Printer for Ontario, 2005

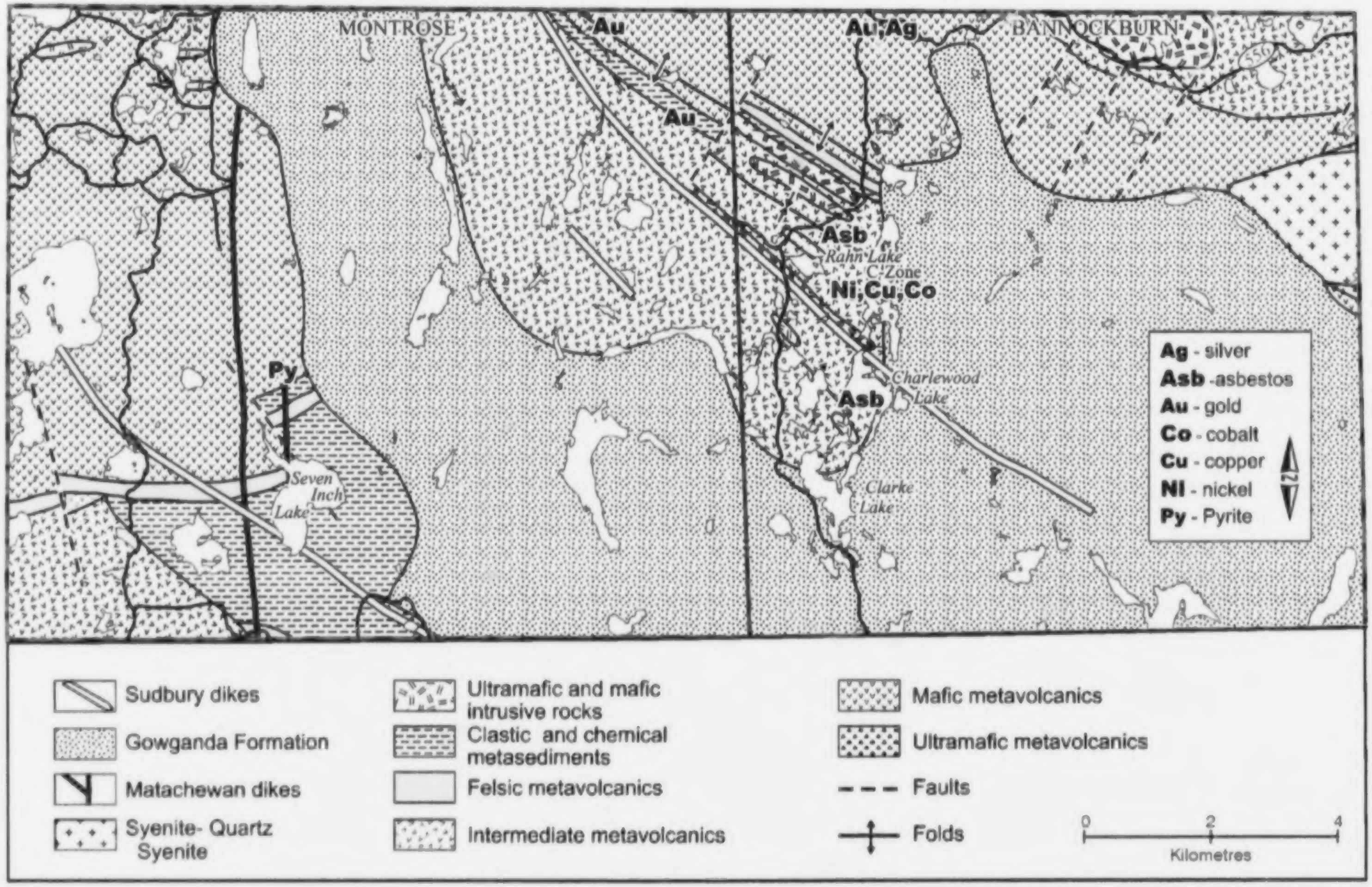

MONTROSE
BANNOCKBURN
Au
Au
Au;Ag
Asb
Rahn Lake
C Zone
Ni,Cu,Co
Charlewood Lake
Asb
Clarke Lake
Py
Seven Inch Lake
550
Ag - silver
Asb -asbestos
Au - gold
Co - cobalt
Cu - copper
Ni - nickel
Py - Pyrite
N
Sudbury dikes
Gowganda Formation
Matachewan dikes
Syenite- Quartz Syenite
Ultramafic and mafic intrusive rocks
Clastic and chemical metasediments
Felsic metavolcanics
Intermediate metavolcanics
Mafic metavolcanics
Ultramafic metavolcanics
Faults
Folds
0
2
4
Kilometres

Figure 6.2. General geology of Bannockburn and Montrose townships.

The Proterozoic Gowganda Formation unconformably overlies the Neoarchean rocks (cf. Lovell 1967; Dyer 1936) and is composed of clastic metasedimentary rocks such as conglomerate, sandstone, wackes and argillites. The Gowganda Formation covers the eastern and southern part of Bannockburn Township as well as the eastern part of Montrose Township and was mapped at reconnaissance scale.

Diabase dikes observed in the mapped are correlated with the Sudbury swarm and the Matachewan swarm (cf. Osmani 1991).

Neoarchean Rocks

MAFIC METAVOLCANIC AND MAFIC INTRUSIVE ROCKS

The mafic metavolcanic rocks found in the northern part of Bannockburn Township and in the western part of Montrose Township are mostly massive and pillowed flows. Kresz (1993) describes similar rocks in the southern part of Argyle Township. The pillows are generally well formed up to 1 m long. The selvage is generally 1 to 5 cm composed of mostly chloritic, and locally carbonated hyaloclastite. The flows are often vesicular and amygdaloidal. The amygdules are mostly composed of chlorite, calcite and rarely quartz. These amygdules indicate a shallow water environment. Varioles are also found in the north west part of Bannockburn Township and on Montrose Lake in Montrose Township. Varioles are generally composed of pyroxene; however, feldspar varioles were observed in the northern part of Bannockburn Township. Flows are locally schistose with pervasive and vein alteration of calcite and epidote. In general, the mafic sequence youngs toward the north in Bannockburn Township and toward the northwest in Montrose Township.

Gabbroic-textured mafic rocks are found throughout both townships. For the most part, these are thought to be part of thick flows. The mafic rocks generally have a dark green colour and may contain up to 5% of pyrite. The magnetic susceptibility of the mafic rocks is variable and correlates well with the airborne geophysical data (OGS 2003).

INTERMEDIATE METAVOLCANIC ROCKS

The intermediate metavolcanic rocks are located in the northeastern corner and in the west-central part of Bannockburn Township as well as the southern part of Montrose Township. They can be divided into 2 subunits: the flows and the fragmental rocks. The flows are either massive or pillowed and are grey green in colour. The massive flows almost always have chlorite amygdules and, more rarely, feldspar and calcite amygdules. Pillows are generally over 1 m long and are irregularly shaped, which makes younging difficult to identify. Selvages are up to 10 cm thick and mostly composed of yellow-green hyaloclastite. Pillowed flows commonly contain up to 50% amygdules and vesicles, the former suggesting a shallow water depositional environment and/or high volatile content within the magmas. The amygdules in the pillows are generally composed of chlorite and feldspar, more rarely calcite and quartz. Gas escape cavities are found throughout the flows and are generally filled with quartz.

The intermediate fragmental rocks are generally unsorted, monolithic tuff breccia with a matrix composed of tuff and lapilli tuff. The fragments vary from 0.5 to 25 cm; they are generally subangular and have the same composition as the matrix. These intermediate rocks are generally nonfoliated and have a pervasive calcite alteration. Feldspar, calcite, chlorite and quartz are the major veins found in this rock type.

INTERMEDIATE INTRUSIVE ROCKS

The central northern part of Bannockburn Township is underlain by a diorite to quartz diorite intrusion. It is generally homogeneous and massive, although some grain size variations were noted locally. It is equigranular and appears to be undeformed. The quartz content may vary and can locally be up to 10%. This dioritic rock may also be associated with an anorthosite that has a "bulls-eye" magnetic high anomaly on the airborne magnetic geophysical map (OGS 2003).

MAFIC TO INTERMEDIATE INTRUSIVE ROCKS

The syenite intrusion (described by Berger and Préfontaine, this volume) is, in major part, situated in Powell Township and terminates in Bannockburn Township. Associated with the syenite are mafic syenites containing approximately 40% amphibole. An extensive epidote, feldspar and garnet alteration occurs at the contact between the mafic metavolcanic rocks and the syenite, which indicates a high-grade contact metamorphic aureole surrounds the intrusion. Hematite, chlorite and sericite are also observed as alterations in that aureole.

METAVOLCANIC AND INTRUSIVE ULTRAMAFIC ROCKS

The ultramafic rocks are situated in the western part of Bannockburn Township and locally in the southeastern part of Montrose Township. They are commonly fragmental, with cumulate clasts, and more rarely spinifex textured. These ultramafic rocks generally have a high magnetic susceptibility; however, some ultramafic rock with low magnetic susceptibility were encountered. Olivine is completely altered to serpentine and magnetite and locally to talc. Veins of asbestos and antigorite crosscut the rocks in a number of places. Field observations and diamond-drill hole data indicate an association between the ultramafic rocks and a leucogabbro found in the Bannockburn Township. This leucogabbro is light grey and massive. Compilation of diamond-drill hole data and airborne geophysical data (OGS 2003) suggests that the northwestern part of Montrose Township may be composed, in part, of ultramafic rocks (Gowest Amalgamated Resources Ltd. and Jonpol Exploration Ltd. 1990; International Nickel Company Ltd. 1976). The drill hole data indicated spinifex texture as well as a serpentine alteration.

METASEDIMENTARY ROCKS

Volcaniclastic metasedimentary rocks underlie the southwest part of Montrose Township. They are mostly matrix supported with angular to subangular felsic clasts up to 20 cm. The matrix is generally composed of a feldspathic tuff to sandy material. Other clasts include chert, wackes and felsic tuff with detrital pyrite. The conglomerate is usually northeasterly foliated, poorly sorted and poorly bedded to massive.

A massive, dark grey chert unit with up to 15% pyrite underlies felsic metavolcanic rocks north of Seveninch Lake (*see* Figure 6.2). The chert is the only exposed part of a metasedimentary package identified by diamond-drill data in southwest Montrose Township (Phelps Dodge Corporation of Canada Ltd. 1986; AMAX Explorations Inc. 1974). Graphite argillite, siltstone and chert extend from Seveninch Lake into Hutt Township and these rocks correspond with airborne electromagnetic anomalies (OGS 2003).

Proterozoic

The Proterozoic sedimentary rocks are part of the Gowganda Formation of the Cobalt Group of the Huronian Supergroup (cf. Lovell 1967; Dyer 1936). These rocks are mostly composed of conglomerate, wacke, argillite and sandstone. They are found in the central and western part of Bannockburn and the western part of Montrose. Polymictic conglomerate is composed of well-rounded clasts of granite, tonalite, quartz vein and metavolcanic rocks that occur in a sandy matrix. The conglomerate is unsorted, poorly bedded and with no internal structure. These conglomerates are generally clast supported with clasts up to 30 cm in diameter, although locally the conglomerate is matrix supported. The wacke is grey on fresh surface and weathers whitish green. It is massive and homogenous. Dropstones up to 70 cm are found in the wacke, although the average size is less than 10 cm and are composed of the same clasts material found in the conglomerate. The argillites are less common and occur with the wacke as convoluted beds. Laminated argillites and wacke, in central Montrose Township, form units up to 5 m thick and are interpreted as varves deposited in a small lake. The sandstones are generally impure quartzite where associated the wacke. However, the sandstone found near the conglomerate is immature with mafic minerals. The sandstones are massive fine to medium grained. Rocks of the Gowganda Formation are generally undeformed and have bedding and lamination indicating a northwesterly dip of 20 to 40°.

DIABASE

Two types of diabase dikes are found in Bannockburn and Montrose townships. Northwest-striking dikes in Bannockburn and Montrose townships cut the Neoarchean rocks and the Gowganda Formation. These diabase dikes, correlated with the Sudbury swarm (Osmani 1991), are characterized by feldspar laths up to 7 cm long and are medium to coarse grained with high magnetic susceptibility.

Diabase dikes correlated with the Matachewan swarm occur only in Montrose Township and are north striking (cf. Osmani 1991).

A series of trenches about 2 km south of the Ashley Mine in Bannockburn Township and expose a unique sequence of rocks in the map area. These trenches show a series of clastic metasedimentary rocks that consist of conglomerates, sandstone, mudstone and argillites. The conglomerates are polymictic and clast supported with sandy beds dispersed throughout. Clasts up to 6 cm in size are composed of chert, felsic metavolcanic and argillite and rare mafic metavolcanic rocks. North of the conglomerate, bedded sandstone and mudstone with load structure and graded beds are found in contact with felsic metavolcanic flow breccia, lapilli tuff and altered pillows. Narrow lamprophyric dikes crosscut the metasedimentary and felsic metavolcanic units. The rocks in these trenches are highly altered with iron carbonate, sericite, green mica, epidote and calcite. These trenches are important because they expose a unique epiclastic marker horizon that marks the boundary between the mafic rocks to the north and the intermediate rocks to the south.

STRUCTURE AND METAMORPHISM

The Neoarchean rocks in the map area are faulted and folded. Structural features are difficult to identify in the field because most of the rocks are very competent and deformation intensity is weak. Spaced cleavages are most common and foliation occurs only in shear zones. Three cleavages were observed. The first cleavage trends at 275° (S_1) and the second at 140° (S_2). However, the dominant cleavage strikes approximately 200° (S_3) and crosscuts all others. A series of faults oriented parallel to the

S_3 occurs in north Bannockburn Township and are characterized by both left and right lateral movement. The faults disrupt the Archean stratigraphy, thus making it difficult to correlate with the units that occur in Powell Township to the east (Berger and Préfontaine, this volume). In the southern part of Montrose Township, faults trend toward the southeast parallel to S_2 cleavage.

The clastic units exposed in the trenches in northwestern Bannockburn Township young to the south, which, in conjunction with north-facing pillows to the north, confirms an anticline fold occurring near the base of the mafic unit. Clastic metasedimentary rocks in the trenches display reversals in stratigraphic facing that indicate F_1 isoclinal folding about axes oriented at 290°. Locally, all three spaced cleavages and their overprinting relationships can be observed; as well, northeast-striking faults with some lateral displacement are also observed.

An area of significant economic interest is the C-zone, a Ni-Cu-Co deposit in ultramafic rocks, reported by Mustang Mineral Corporation. This zone is situated near Rahn Lake in the western part of Bannockburn Township. Variations in the surrounding ultramafic and intermediate metavolcanic rocks suggest this area is tightly folded around an axis parallel to S_1 cleavage and faulted with lateral displacement parallel to the S_3. This hypothesis is supported by airborne magnetic geophysical data (OGS 2003). Most of the deformation in this area, however, is confined to the massive sulphides and the ultramafic rocks, which are locally schistose.

In general, the metamorphism is low-grade greenschist. Most of the rocks have secondary amphibole as well as chlorite. Locally, however, the metamorphism grades up to upper greenschist with the epidote and garnet metamorphic assemblages. This is only found near the syenite in Bannockburn Township and is interpreted as the effect of contact metamorphism.

RECOMMENDATIONS FOR EXPLORATION

Mustang Mineral Corporation discovered Ni-Cu-Co mineralization in the western part of Bannockburn Township in 2003. This deposit (C-zone) occurs at the bottom of an ultramafic unit and this unit should be explored in detail for additional mineralization. The C-zone is coincident with a magnetic high that is perpendicular to the main magnetic trend in this area. Perhaps, other magnetic highs perpendicular to the regional trend may also contain sulphides (OGS 2003).

A high gravity anomaly is situated east of Charlewood Lake and Clarke Lake under rocks of the Gowganda Formation (OGS 2003). This anomaly may be related to ultramafic rocks and presents an attractive exploration target for Ni-Cu-Co mineralization similar to the Rahn Lake area.

Little exploration has been done in northern Montrose Township. This area is extensively covered with Quaternary sediments. Ultramafic rocks occur both in northern and southern Montrose Township neither of which have been thoroughly explored for Ni-Cu-Co-PGE mineralization.

Several gold showings are found in the northwestern part of Bannockburn Township and in the northeastern part of Montrose Township including the past-producing Ashley Mine. All the showings are in quartz veins accompanied by iron carbonate alteration. Widespread carbonate alteration and quartz veining indicates more exploration is warranted in this area.

A shear zone located in the northeast part of Bannockburn Township has extensive iron carbonate, sericite and green mica alteration and is an attractive target for gold exploration.

REFERENCES

AMAX Explorations Inc. 1974. Diamond drill record, Montrose Township; Kirkland Lake Resident Geologist office, assessment file # KL-034.

Cooke, H.C. 1919. Geology of Matachewan District, northern Ontario; Geological Survey of Canada, Memoir 115, 60p.

Dyer, W.S. 1936. Geology and ore deposits of the Matachewan–Kenogami area; Ontario Department of Mines, Annual Report, 1935, v.44, pt.2, p.1-55.

Gowest Amalgamated Resources Ltd. and Jonpol Exploration Ltd. 1990. Geophysical survey and diamond drilling on the property of Gowest Amalgamated Ltd. and Jonpol Exploration Ltd., Montrose Township, Ontario; Kirkland Lake Resident Geologist office, assessment file # KL-2922.

International Nickel Company Ltd. 1976. Diamond drill log, Montrose and Hutt townships; Kirkland Lake Resident Geologist office, assessment file # KL-1279.

Jensen, L.S. 1996. Precambrian geology of Montrose Township; Ontario Geological Survey, Preliminary Map P.3354, scale 1:20 000.

——— 1996. Precambrian geology of Bannockburn Township; Ontario Geological Survey, Preliminary Map P.3355, scale 1:20 000.

Kresz, D.U. 1993. Geology of Argyle and Baden townships; Ontario Geological Survey, Open File Report 5874, 114p.

Lovell, H.L. 1967. Geology of the Matachewan area; Ontario Department of Mines, Geological Report 51, 61p. Accompanied by coloured maps 2109, 2110, scale 1:31 680.

Ontario Geological Survey 2003. Ontario airborne geophysical surveys, magnetic and electromagnetic data, grid and vector data and profile data, Kirkland Lake area; Ontario Geological Survey, Geophysical Data Set 1102–Revised.

Osmani, I.A. 1991. Proterozoic mafic dike swarms in the Superior Province of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.661-681.

Phelps Dodge Corporation of Canada Ltd. 1986. Log of diamond drill, Montrose Township; Kirkland Lake Resident Geologist office, assessment file # KL-2266.

Rickaby, H.C. 1932. Bannockburn gold area; Ontario Department of Mines, v.41, pt.2, p.1-24. Accompanied by Map 41A Bannockburn gold area, scale 1:47 520.

7. Project Unit 05-004. Physical Volcanology and Economic Potential of Komatiite-Associated Ni-Cu-(PGE) Deposits, Bannockburn Township Area

M.G. Houlé[1,2,3], S. Préfontaine[1] and B.R. Berger[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Mineral Exploration Research Centre and Department of Earth Sciences, Laurentian University, Sudbury, Ontario
[3]Ottawa–Carleton Geoscience Centre and Department of Geology, University of Ottawa, Ottawa

---

INTRODUCTION

The Precambrian Geoscience Section of the Ontario Geological Survey (OGS) conducted bedrock mapping, at a scale of 1:20 000, in Cairo Township in 2002 (Berger and Leblanc 2002) and in Montrose, Bannockburn and Powell townships in 2005 (Berger and Préfontaine, this volume; Préfontaine and Berger, this volume) as part of an ongoing project to update geological mapping in the Matachewan area. The goal of this contribution is to complement the Ontario Geological Survey bedrock mapping project in assessing the distribution, the physical volcanology and the economic potential of the komatiitic rocks in this area.

GENERAL GEOLOGY

The Bannockburn Township area is located west of Matachewan in the southern part of the western Abitibi greenstone belt. The map area is underlain by Neoarchean ultramafic, mafic, intermediate and felsic metavolcanic rocks and clastic metasedimentary rocks. Several intrusions occur through the supracrustal rocks and are dominated by ultramafic to mafic intrusions and alkalic intrusions (syenite, feldspar porphyry) and mafic to intermediate intrusions (gabbro, quartz diorite) (Figures 7.1 and 7.2).

Clastic sedimentary rocks cover a large part of the map area and are correlated with the Proterozoic Gowganda Formation of the Cobalt Group of the Huronian Supergroup that unconformably overlies the Archean rocks. Diabase dikes observed in the mapped area are attributed to the Sudbury and Matachewan swarms.

Four major faults crosscut the Bannockburn area at high to moderate angles with the stratigraphy: the Cadillac–Larder Lake deformation zone and the Galer Lake fault trending southwest to northeast and the Mistinikon Lake fault and the Montreal River fault trending north to south. The reader is referred to Berger and Préfontaine (this volume: Powell Township), Préfontaine and Berger (this volume: Montrose and Bannockburn townships); and Berger and Leblanc (2002) and Leblanc and Berger (2003: Cairo Township) for a more detailed geological context.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.7-1 to 7-18.

© Queen's Printer for Ontario, 2005

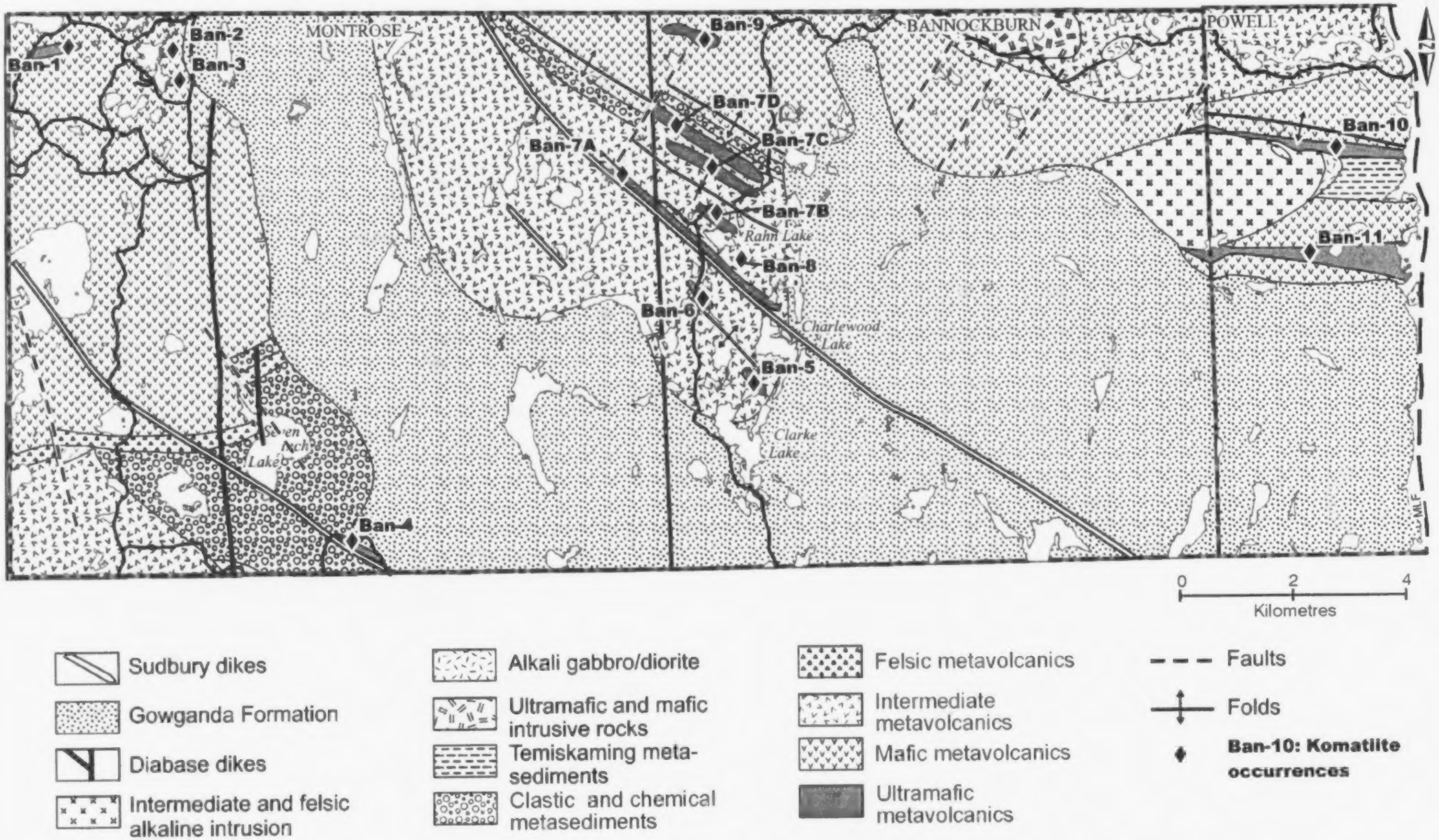

MONTROSE
BANNOCKBURN
POWELL
N
MLF
Ban-1
Ban-2
Ban-3
Ban-9
Ban-7D
Ban-7C
Ban-7A
Ban-7B
Rahn Lake
Ban-8
Ban-6
Charlewood Lake
Ban-5
Clarke Lake
Seven Inch Lake
Ban-4
Ban-10
Ban-11
0
2
4
Kilometres
Sudbury dikes
Gowganda Formation
Diabase dikes
Intermediate and felsic alkaline intrusion
Alkali gabbro/diorite
Ultramafic and mafic intrusive rocks
Temiskaming meta-sediments
Clastic and chemical metasediments
Felsic metavolcanics
Intermediate metavolcanics
Mafic metavolcanics
Ultramafic metavolcanics
Faults
Folds
Ban-10: Komatiite occurrences

Figure 7.1. General geology of Montrose, Bannockburn, and part of Powell townships (*adapted from* Berger and Préfontaine, this volume; and Préfontaine and Berger, this volume).

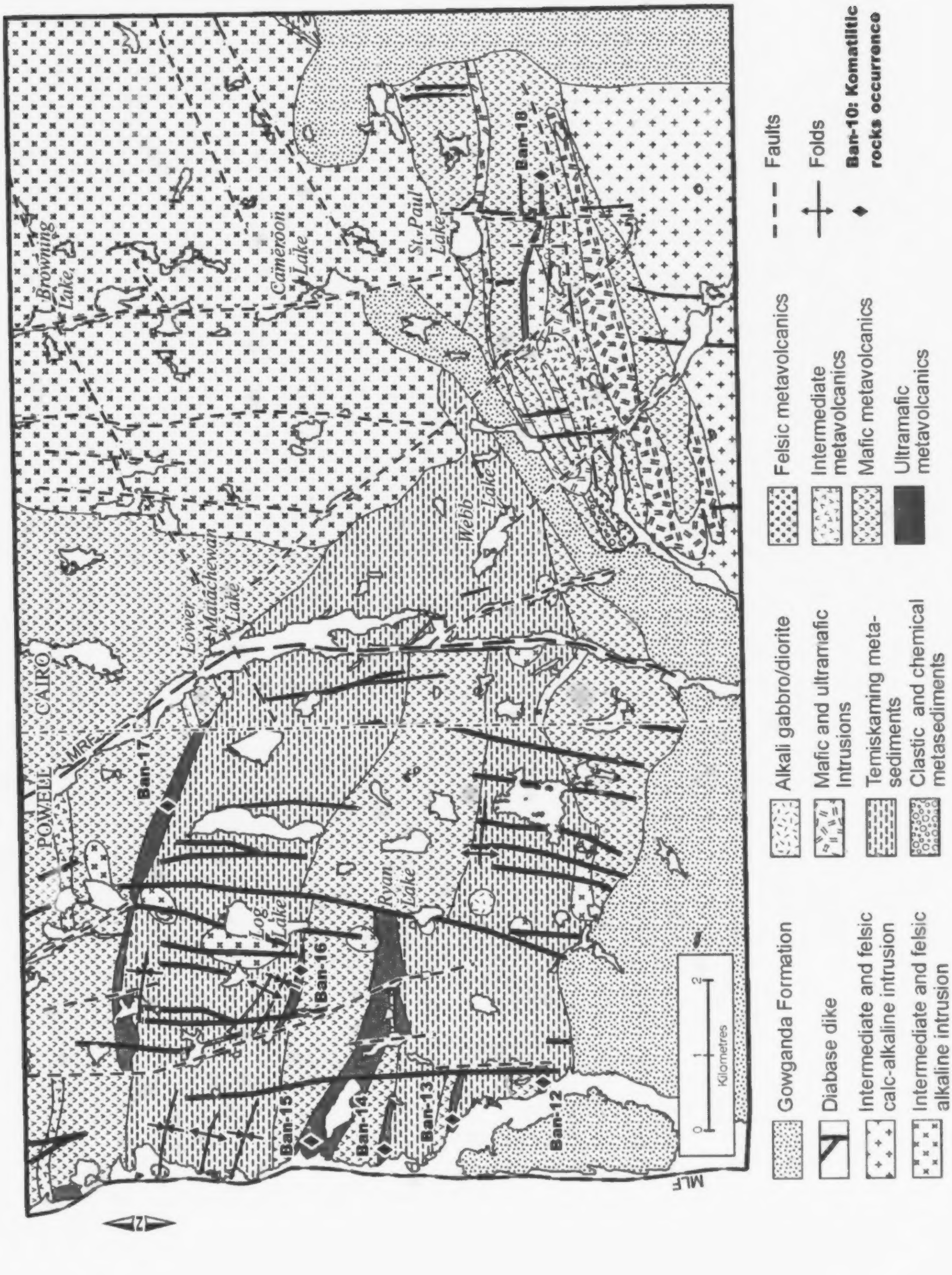

N
Browning Lake
Cameroon Lake
St. Paul Lake
Webb Lake
Lower Matachewan Lake
Ryan Lake
Log Lake
CAIRO
POWELL
MRF
MLF
Ban-12
Ban-13
Ban-14
Ban-15
Ban-16
Ban-17
Ban-18
0 1 2
Kilometres
Gowganda Formation
Diabase dike
Intermediate and felsic calc-alkaline intrusion
Intermediate and felsic alkaline intrusion
Alkali gabbro/diorite
Mafic and ultramafic intrusions
Temiskaming metasediments
Clastic and chemical metasediments
Felsic metavolcanics
Intermediate metavolcanics
Mafic metavolcanics
Ultramafic metavolcanics
Faults
Folds
Ban-10: Komatiitic rocks occurrence

Figure 7.2. General geology of Cairo and part of Powell townships (*adapted from* Berger and Préfontaine, this volume; and Berger and Leblanc 2002).

EXPLORATION HISTORY

Nickel-copper-(platinum group element) (PGE) discoveries in the Abitibi greenstone belt (AGB) occurred sporadically, including several periods of intense exploration and discovery alternating with other periods with only minimal mineral exploration (Ayer et al. 2005). Thus, Ni-Cu-(PGE) mineralization continues to be discovered whenever there is sufficient exploration activity.

The Bannockburn area is not an exception in the AGB; before 1995, little nickel exploration was conducted in this area and was essentially recognized for its gold potential (e.g., Ashley gold mine: ~50 000 ounces Au). Before 1995, ultramafic rocks in this area were targeted for their asbestos potential, for example, in the late 1930's, late 1960's and early 1970's, respectively, by the Asbestos Company Limited and by Canex Aerial Exploration Limited. Outokumpu Mines Ltd. undertook an intense exploration program (e.g., geophysical surveys, surface geological mapping, various geochemical surveys, and diamond drilling) between 1995 and 1999 on the property to assess the potential for komatiite-associated Ni-Cu-(PGE) deposits (*see* Harron 2005 for more detailed descriptions). Much of the significant known komatiite-associated Ni-Cu-(PGE) mineralization in this area was discovered by Outokumpu Mines Ltd. during this intense exploration (Thalweg: 1996; Bannockburn: 1998; Rahn Lake: 1998). Since acquiring the property in 2003, Mustang Minerals Corp. has completed a large exploration program (e.g., geophysical surveys, assays, and diamond drilling) that focussed on previous known occurrences and on new targets generated by geophysical surveys (Harron 2005). One of the most recent discovery of komatiite-associated Ni-Cu-(PGE) mineralization (C-Zone–C Offset: 2003) in the Abitibi greenstone belt was found by this exploration program.

KOMATIITIC ROCKS WITHIN THE BANNOCKBURN AREA

In the following section, the map area is divided into three blocks based on geological context (map patterns) and major breaks: the *Montrose–Bannockburn Block*, the *Powell Block*, and the *Cairo Block* (*see* Figure 7.1 and 7.2). The Montrose–Bannockburn Block corresponds to the area located west of the Mistinikon Lake fault. The Powell Block corresponds to the area located between the Mistinikon Lake fault and the Montreal River fault. The Cairo Block corresponds to the area located east of the Montreal River fault. Komatiitic rocks occur in different proportions in each of these blocks. Table 7.1 summarizes the distribution and the komatiite volcanological facies in the map area.

Distribution and Volcanological Facies of Komatiitic Rocks

MONTROSE–BANNOCKBURN BLOCK

Komatiitic rocks are relatively abundant in the Montrose–Bannockburn Block and are composed of up to 4% of the supracrustal rocks. All komatiitic rock outcrops in this block are distributed over eleven komatiite occurrences (from Ban-1 to Ban-11: *see* Figure 7.1). Only three komatiite occurrences (Ban-5, 7 and 8) possess enough exposure to evaluate their textural facies variations. These komatiite occurrences correspond, respectively, to the Thalweg Zone, the Bannockburn–Rahn Lake Zone, and the C-Zone. Overall, the komatiitic rocks in this sector exhibit several different textural facies such as massive (aphyric and cumulate), spinifex texture, flow breccia, and polysutured jointing. In the Montrose–Bannockburn Block, massive cumulate komatiite and lesser massive aphyric komatiite are the dominant textural facies that occur throughout the area.

Table 7.1. Summary of the komatiitic rocks in the Bannockburn area.

ID	Area	Type	Rock Type	Width (m)	Komatiite Facies					Sulphides	
					Textural	Lithofacies	Morphofacies	Units	Volcanic	Species	Showing
Ban-01	Mont-Ban Block	C	Kk, Kb	180	Ma[Cu], OSx, PSx	UN, DC	Shl?	M	DSF/S	N.O.	N.K.
Ban-02	Mont-Ban Block	C	Kr	130	Ma, Sx	UN, DN	Pw, Shl?	M	DSF/S	N.O.	N.K.
Ban-03	Mont-Ban Block	C	Kr	115	Ma[Cu], Sx	UC, DC	Shl?, Pw	M	DSF/S	Py	N.K.
Ban-04	Mont-Ban Block	O	Kk	200	Ma, Sx	DN	Shl	M	USF/S	N.O.	N.K
Ban-05	Mont-Ban Block	O	KPd, Kk	20-300	Ma[Cu], Sx	UC, DN	Sh	M	CSF/S	Po, Pn	Thalweg
Ban-06	Mont-Ban Block	O	KPd	80	Ma[Cu]	UC	Sh	S	USS	N.O.	N.K
Ban-07	Mont-Ban Block	O	KPd, KDn, Kk	50-250	Ma[Cu], Sx, Fbx	UC, DC, DN	Sh	M	CSF/S	Po, Pn.	Bannockburn, Rahn Lake
Ban-08	Mont-Ban Block	O	Kk, KPd	10	Ma[Cu], Fbx	UC	Sh	M	USD	Po, Pn.	C-Zone, C-Offset
Ban-09	Mont-Ban Block	O	Kk	180	Sx, Vr	DN	Shl	M	TDF	N.O.	N.K
Ban-10	Mont-Ban Block	O	Kk	50-230	Sx, Fbx, Pj, Ma	DN	Shl	M	TDF	N.O.	N.K
Ban-11	Powell Block	O	Kk	90-650	Ma,Pj, Fbx	UN	Shl	M	CSF	Py	?
Ban-12	Powell Block	G	Kr	130	-	-	-	-	-	-	N.K
Ban-13	Powell Block	O	Kk	50-90	Ma, Fbx	UN	Shl	M-S	TUF	N.O.	N.K
Ban-14	Powell Block	G	Kr	70-140	-	-	-	-	-	-	N.K
Ban-15	Powell Block	O	Kk, KPd	80-500	Ma[Cu], Ly, Fbx, Sx, Pj	UC, DN	Sh	M	CSF	N.O.	N.K
Ban-16	Powell Block	O	Kk	50-130	Fbx	UN	Shl	M-S	TUF	N.O	N.K
Ban-17	Powell Block	O	Kk, KPd, KPx	50-200	Ma,Fbx	UN, DC	Shl	M-S	CSF	N.O.	N.K.
Ban-18	Cairo Block	O	Kb		Ma[Cu], PSx, Hy	UC, DN	Shl	M	TDF	Sulph	N.K.

ID: komatiitic occurrence; Mont-Ban Block: Montrose-Bannockburn Block; **Type:** data acquisition, O: Observed, C: Compiled, G: Geophysical; **Width:** Thickness of the komatiitic occurrence; **Textural -** Ma: Massive, Cu: Cumulate, Sx: Spinifex, OSx: Olivine spinifex, PSx: Pyroxene spinifex, Fbx: Flow/magmatic breccia, Vr: Variolitic, Pj: Polysutured jointing; **Lithofacies –** UN: Undifferentiated Non-cumulate, UC: : Undifferentiated Cumulate, DN: Differentiated Non-cumulate, DC: Differentiated Cumulate; **Morphofacies –** Shl: Sheet-like, Sh: Sheet, Pw: Pillowed; **Volcanic –** DSF/S: Differentiated Sheet Flow/Sill, CSF/S: Channelized Sheet Flow/Sill, USF/S: Undifferentiated Sheet Flow/Sill, USD: Undifferentiated Sheet Dike, TDF: Thin Differentiated Flow, TUF: Thin Undifferentiated Flow; **Species -** Po: Pyrrhotite, Pn: Pentlandite, Py: Pyrite; **N.O.:** Not observed, **N.K.:** Not known.

Bannockburn–Rahn Lake–C-Zone Area

The Bannockburn–Rahn Lake–C-Zone komatiite occurrences (Ban-7 and Ban-8) represent most of the komatiite occurrences in the western half of Bannockburn Township. Figure 7.3 shows a simplified geological map of this area and represents a preliminary geological interpretation based on field data and diamond drill core data from Outokumpu Mines and Mustang Minerals. Recent work conducted by the OGS (Préfontaine and Berger, this volume; this contribution) increase our knowledge of this area, however, our understanding is incomplete and many questions remain.

The Bannockburn Zone (Ban-7A) is composed of thick zones of komatiitic dunite and komatiitic peridotite with lesser and thinner komatiitic pyroxenite and komatiitic gabbroic zones. Minor spinifex zones also occur at the top of the unit. The Rahn Lake Zone (Ban-7B) is composed of thick intervals of komatiitic peridotite with lesser and thinner komatiitic pyroxenite and rare gabbroic zones. Common spinifex zones occur within and at the top of the units. The C-Zone (Ban-8) is composed of thin zones of komatiitic peridotite overlain by thin zones of komatiitic pyroxenite and komatiitic breccias. Minor pyroxene spinifex zones also occur locally towards the top of the unit.

The Rahn Lake sector is a key area to try to understand the komatiitic architecture of the map area (*see* Figure 7.3) because elsewhere the komatiite occurrences are not well exposed and/or are composed of undifferentiated homogeneous komatiitic units.

On the northwest side of Rahn Lake, the komatiitic unit dips moderately to the southwest at 65° and is overlain by dacite metavolcanic rocks. The komatiitic unit is composed of an autoclastic sorted breccia containing rounded to subangular fragments of komatiite within an altered komatiitic matrix. Further south along the shoreline of Rahn Lake, a diamond-drill hole intersected the same contact exhibiting well-developed spinifex zones overlain by dacitic metavolcanic rocks suggesting a southwest-facing direction.

On the south side of Rahn Lake, the komatiitic unit is moderately dipping to the north-northeast at 65° and is overlain by dacite metavolcanic rocks. Here, the komatiitic unit is composed of an autoclastic sorted breccia containing rounded to subangular fragments of cumulate komatiite within an altered komatiitic matrix (*see* Figure 7.3; Photo 7.1A). Some of the cumulate fragments contain disseminated sulphides. Locally below this contact zone, the komatiitic peridotite is highly serpentinized (*see* Figure 7.3; Photo 7.1B). Following the same contact further south, the upper part of the komatiite unit exhibits a spinifex breccia to coherent olivine spinifex zone that contains several rounded cumulate komatiite fragments (*see* Figure 7.3; Photo 7.1C). In this location, the komatiite unit is moderately to steeply dipping toward the northeast, overlain by the C-Zone footwall suggesting a facing direction to the northeast.

At the stripped area (C-Zone), the komatiitic unit trends 070° and dips steeply to the south-southeast. This unit appear to be discordant (*see* Figure 7.3) with the surrounding rocks (dacitic and komatiitic rocks) and is facing to the southeast based on the distribution of the mineralization and rare spinifex-bearing rocks. Most of the upper third of the komatiitic unit is composed of poorly sorted (fragments size from 1 to 60 cm) komatiite breccia (autoclastic) containing rounded to subangular fragments of phyric to cumulate komatiite, aphyric komatiite, and spinifex-bearing komatiite within an altered komatiitic matrix (*see* Figure 7.3; Photo 7.1D). Furthermore, volcanic structures such as pillow-like structure, "volcanic" breccias along those structures, and scattered highly vesicular zones overlying the komatiite breccias in the central part of the C-Zone strongly suggest at least limited interaction with seawater on the seafloor or subseafloor.

Difficulties in the interpretation of the geological context around Rahn Lake resulted from several factors such as the major komatiitic units of this sector trending northwest to southeast with some reverse facing directions (northwest and south side of Rahn Lake), the presence of a discordant komatiitic unit (C-Zone) and the general lack of bedding and facing directions within the surrounding dacitic volcanic rocks.

Several hypotheses may be considered to explain the actual discordant nature of the C-Zone in the geological complexity of the Rahn Lake area, including structural emplacement (i.e., fault-bounded emplacement), komatiite flow or sill lying within a southeast-closing fold hinge, or a primary emplacement that preserved or at least partially preserved angular relationships between the C-Zone and the Rahn Lake komatiite. Evidence of interaction between the komatiite and the dacitic footwall observed on the stripped area (*see* Photos 7.4A and 7.4B) combined with a northeast-facing direction for the Rahn Lake komatiite located south of the C-Zone strongly disproves a structural emplacement hypothesis. The possibility that the C-Zone is lying within a southeast to east fold hinge is unlikely because it does not

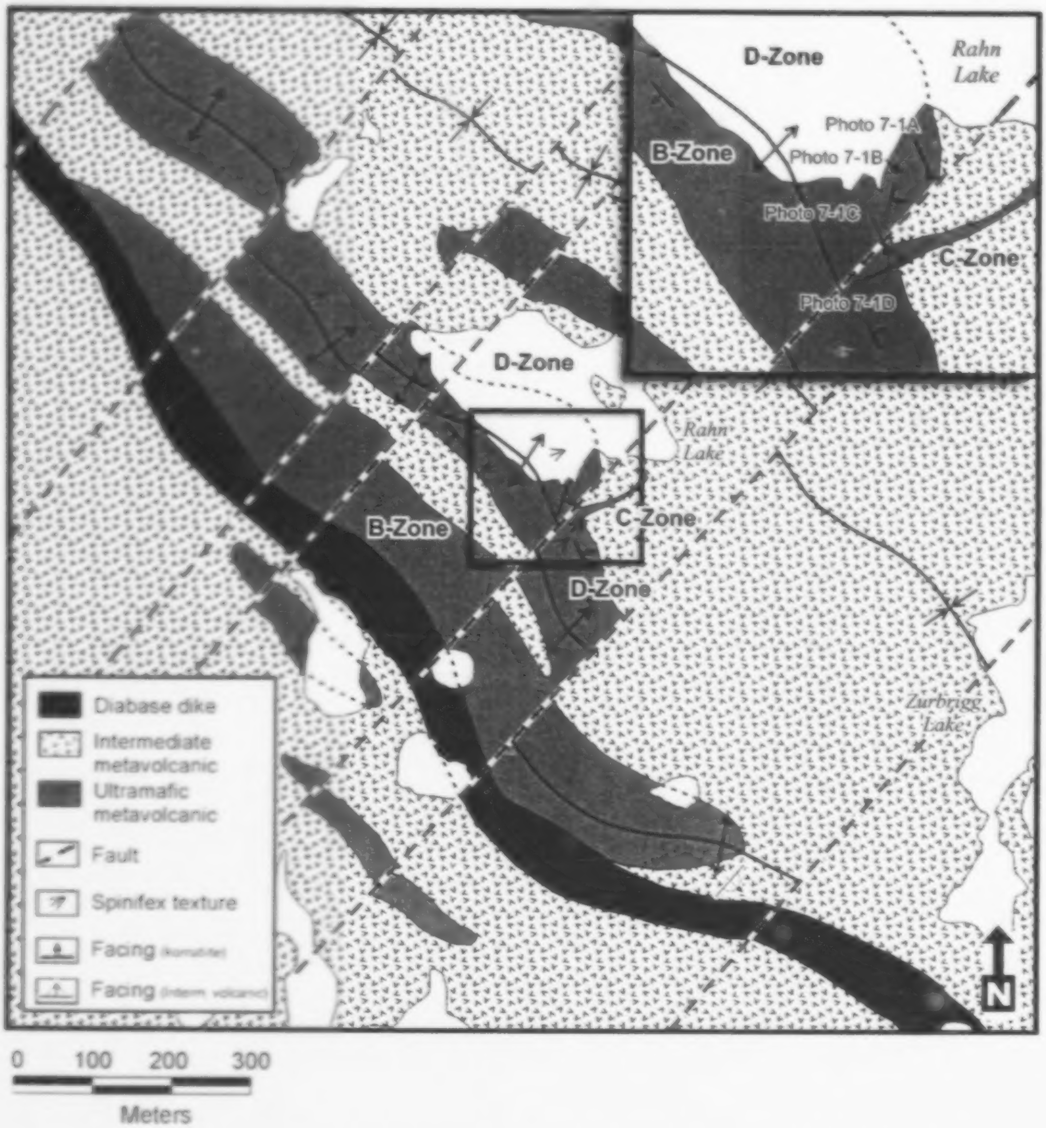

D-Zone
Rahn Lake
Photo 7-1A
B-Zone
Photo 7-1B
Photo 7-1C
C-Zone
Photo 7-1D
D-Zone
Rahn Lake
B-Zone
C-Zone
D-Zone
Zurbrigg Lake
Diabase dike
Intermediate metavolcanic
Ultramafic metavolcanic
Fault
Spinifex texture
Facing (komatiite)
Facing (interm. volcanic)
N
0
100
200
300
Meters

Figure 7.3. Sketch map of the surface geology in the area of the Bannockburn–Rahn Lake–C-Zone in Bannockburn Township. This preliminary interpretation of the geological context of this area is based essentially on surface geology with some insights from diamond drilling conducted by Outokumpu Mines Ltd. in the mid 1990s and, more recently, by Mustang Minerals.

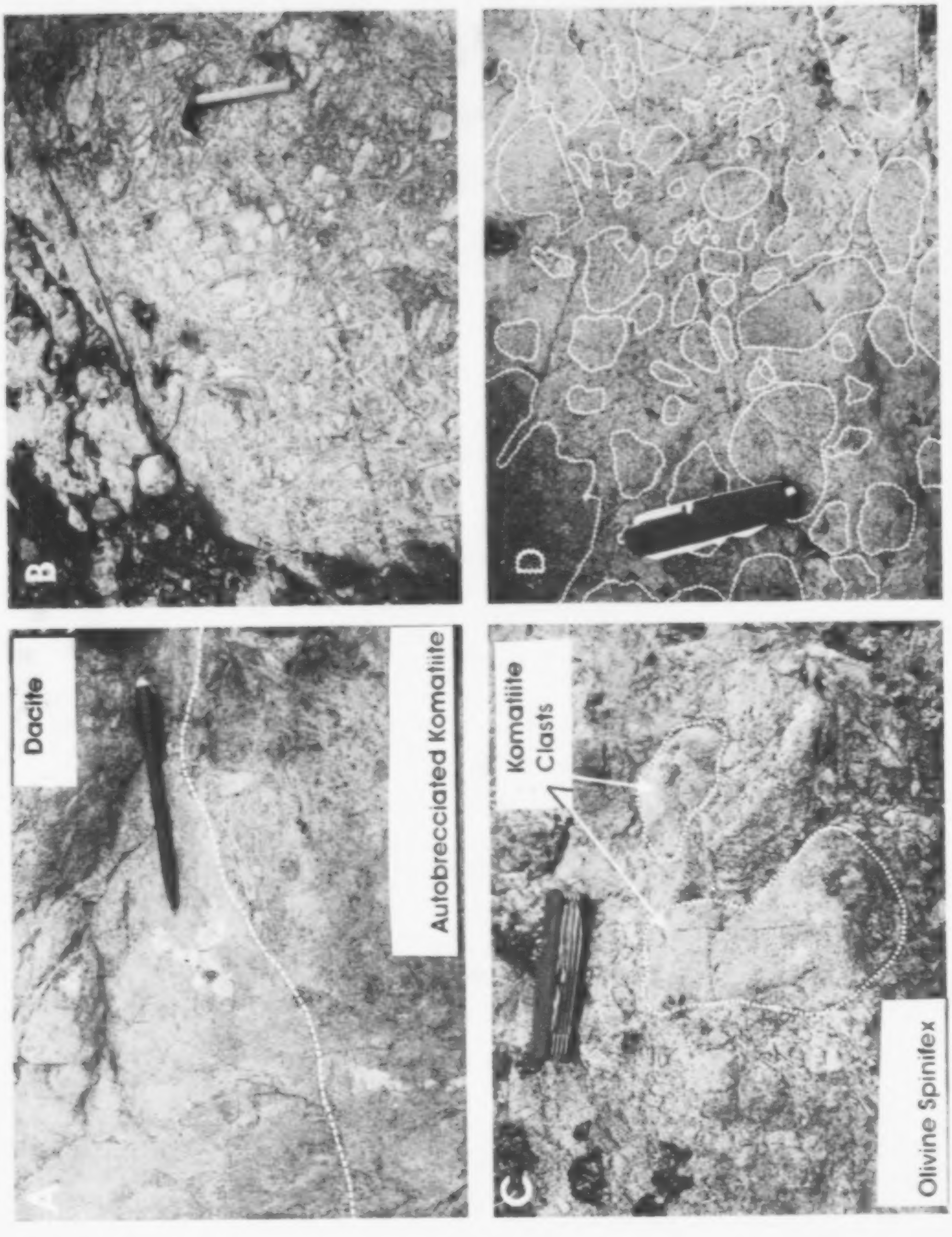

A
Dacite
Autobrecciated Komatiite
B
C
Komatiite
Clasts
Olivine Spinifex
D

Photo 7.1. A) Contact between autobrecciated komatiitic peridotite of the Rahn Lake Zone and the dacite of the footwall of the C-Zone. B) Highly serpentinized komatiitic peridotite of the Rahn Lake Zone. C) Cumulate komatiite fragment within the spinifex-textured upper part of the Rahn Lake komatiitic peridotite. D) Autobrecciated komatiite upper zone of the C-Zone komatiitic peridotite from the western edge of the stripped area. Phyric to cumulate texture are the dominant textural facies for the fragments but some spinifex-bearing fragments also occurred.

seem to fit the overall fold pattern in this area. Based mainly on this discordant nature, we suggest that the C-Zone is most likely an inclined dike. However, the true nature of the C-Zone komatiitic unit may be best determined by careful examination of the diamond-drill core that intersected both contacts (but especially the upper contact) with the host volcanic rocks.

Thalweg Area

The Thalweg komatiite occurrence (Ban-5) is completely isolated from other komatiite occurrences in the western half of Bannockburn Township. Figure 7.4 shows a simplified geological interpretation of the Thalweg area based on field data and diamond-drill core data from Outokumpu Mines and Mustang Minerals. The Thalweg komatiite occurrence has a facing direction toward the northeast and contains at least four different komatiite units hosted in massive dacitic metavolcanic rocks. Limited iron formations are also present underlying the main komatiite unit. This sequence represents a typical channelized sheet flow or sill environment where the Thalweg sulphide mineralization occurs at the base of an embayment. The main komatiite unit is composed of thick olivine adcumulate to mesocumulate rocks, whereas the flanking facies north and south of the sulphide mineralization are thinner and more differentiated units containing spinifex-bearing komatiite. This unit has a strike length of over 1 km and varies in thickness from 100 to 150 m in the middle of the embayment to less than 30 m in the flanking area. The lateral extent of this occurrence is unknown because the southern margin is covered by the Gowganda Formation. The basal contact of this channelized sheet flow or sill environment is characterized by an extensive and complex branching out of thin komatiitic units into the footwall. The stripped area has exposed some thin komatiitic units beneath the main komatiite unit displays that complexity (Photo 7.2). The upper part of this komatiitic sequence is characterized by numerous and thin differentiated komatiitic units intercalated with dacitic flows. The geology is further complicated by a network of interpreted faults trending approximately 070° that disrupt and displace the komatiite units. The presence of some komatiitic units directly beneath some dacitic exposures, combined with contacts dipping to the northwest (*see* Figure 7.2), suggests that the komatiitic sequence is overturned and dips to the west. This speculation appears to be confirmed by the magnetic survey (P. Wood, Mustang Minerals Corp., personal communication, 2005).

POWELL BLOCK

Komatiitic rocks are relatively abundant in the Powell Block and comprise up to 5% of the supracrustal rocks. Most of the komatiitic rocks which outcrop in this block occur in the six labelled komatiite occurrences (from Ban-12 to Ban-17: *see* Figure 7.2). However, there are numerous other komatiitic outcrops that are not large enough to merit their own occurrence label at this scale. These units are intimately intercalated with mafic metavolcanic rocks in the central and southern parts of the Powell Block. Only two komatiite occurrences (Ban-15 and Ban-17) are sufficiently exposed to evaluate their textural facies variations. Ban-15 is located in the central part of the Powell Block and is in contact with Timiskaming metasedimentary rocks and mafic metavolcanic rocks to the south and in contact with mafic metavolcanic rocks to the north. This komatiite occurrence varies in thickness from 80 to 500 m and is composed of multiple cooling units of komatiite and cumulate komatiite trending northwest to southeast over 3.6 km. Ban-15 shows textural facies variation along strike exhibiting massive komatiitic peridotite cumulate in the eastern part to more differentiated units (i.e., massive, spinifex, flow breccia, and layered flows [massive/spinifex]) in the western part. Ban-17 is located in the northern part of the Powell Block and is in contact with Timiskaming metasedimentary rocks to the south and mafic metavolcanic rocks to the north. This komatiite occurrence varies in thickness from 50 to 200 m and is composed of multiple cooling units of komatiite and cumulate komatiite trending northwest to southeast for over 4.5 km. Ban-17 shows a textural facies variation along strike that mirrors Ban-15, with komatiitic peridotite and pyroxenite in the western part and more differentiated units (massive, flow breccia) in the eastern part.

Overall, the komatiitic rocks in this sector exhibit several different textural facies such as massive (aphyric and cumulate), spinifex texture, flow breccia, and polysutured jointing. In the Powell Block, the flow breccia textural facies (e.g., flow breccia, flow-top breccia, hyaloclastite) are well distributed throughout most of the komatiite occurrences and komatiitic outcrops.

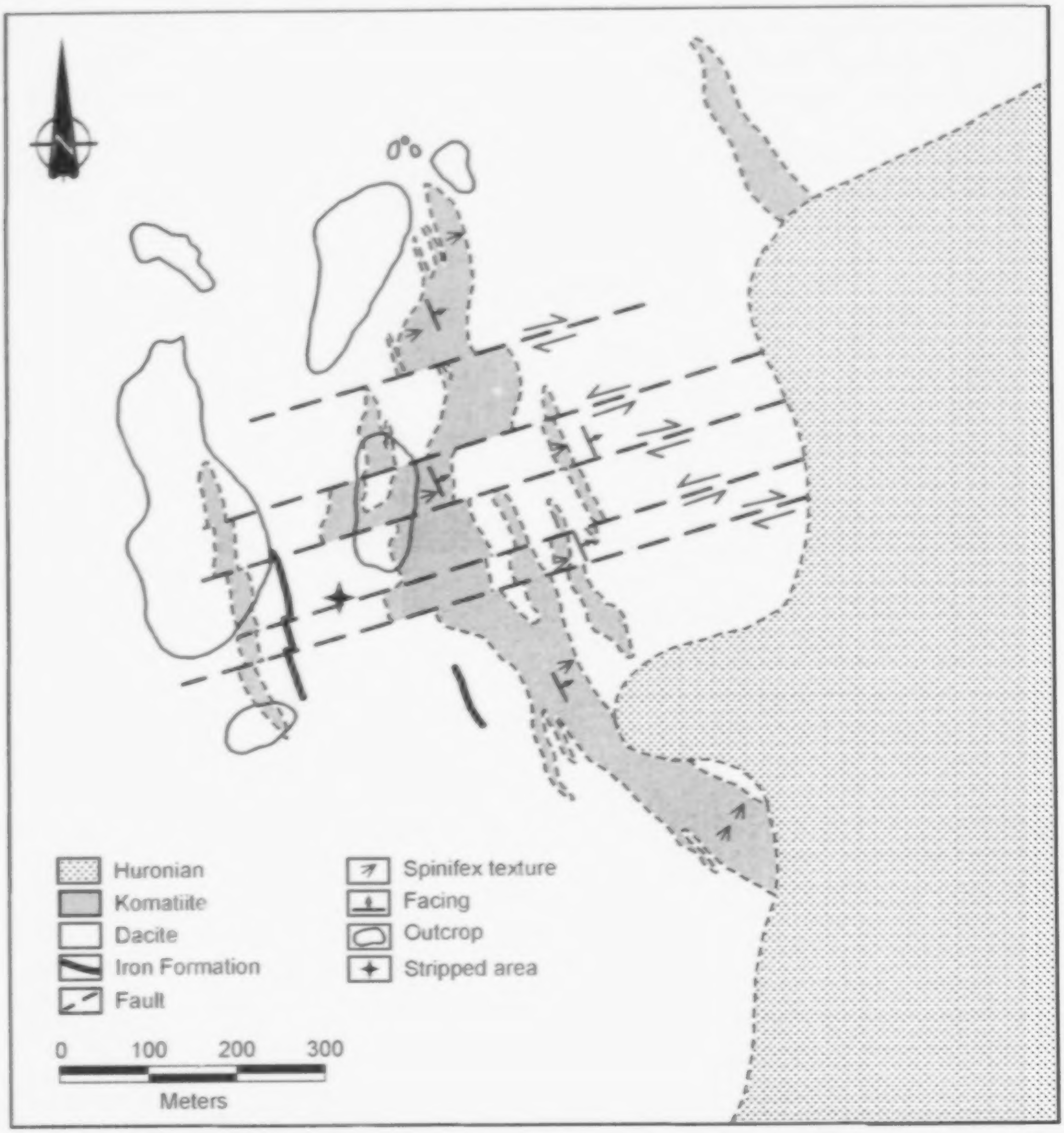

Huronian
Komatiite
Dacite
Iron Formation
Fault
Spinifex texture
Facing
Outcrop
Stripped area
0
100
200
300
Meters

Figure 7.4. Simplified geological map of the Thalweg area based on projection to the surface of data from some of the diamond-drilling programs conducted by Outokumpu Mines and Mustang Minerals. Note that some of the komatiitic units projected to the surface are located directly underneath intermediate metavolcanic outcrops. This reconstruction is based on information extracted from the diamond-drill logs. The diamond-drill cores from Outokumpu Mines are no longer available.

CAIRO BLOCK

The komatiitic rocks in the Cairo Block represent only a small proportion of the rock units observed during the regional bedrock mapping in 2002 by Leblanc and Berger (2003). Only one komatiite occurrence is labelled in this area (Ban-18: *see* Figure 7.2). It crops out along the powerline south of St. Paul Lake. This komatiitic occurrence varies in thickness from 40 to 70 m and is composed dominantly of komatiitic basalt trending east to west for over 2.3 km. From west to east, this unit is in contact with alkali granite and quartz syenite, sulphide-graphite-facies iron formation, massive and autobrecciated intermediate volcanic rocks, and massive and variolitic mafic volcanic rocks along the southern contact (footwall), whereas it is in contact with massive mafic volcanic rocks along its northern contact (hanging wall).

Komatiitic basalt exhibits pale orange-brown to bone-white weathered surfaces and dark green or pale green fresh surfaces. Most exposures around the Whiskeyjack Creek fault consist of massive and sheared komatiitic basalt (western part), whereas most of the exposure in the eastern part consists of fine-grained olivine cumulate, pyroxene spinifex-bearing rocks and *in situ* komatiitic hyaloclastite. Banded iron formation is locally incorporated as xenoliths in an exposure of komatiitic basalt located under the powerline south of St. Paul Lake (Photo 7.3A). An abundance of jigsaw-fit *in situ* hyaloclastite with an intense alteration of the clast margins (Photo 7.3B) suggests a high water:rock interaction ratio between seawater and the komatiitic basalt flow. Furthermore, the presence of a highly vesiculated komatiitic basalt margin along the contact with the xenoliths (Photo 7.3C) also suggests that the iron formation was not completely consolidated. Partial assimilation of the iron formation is also suggested by the low magnesium content of these rocks.

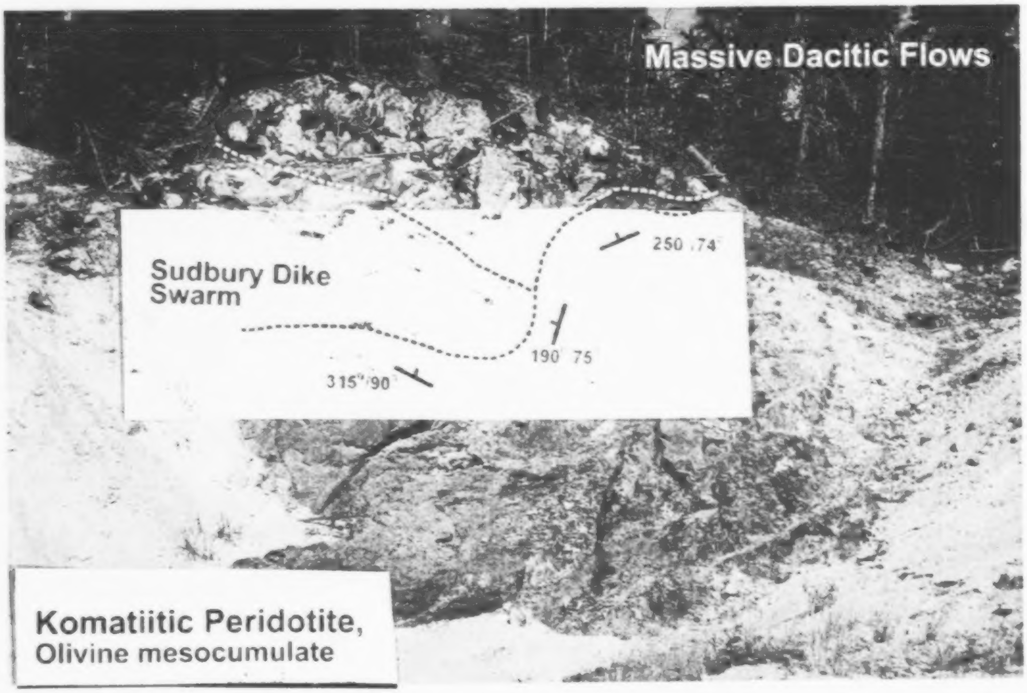


Photo 7.2. Eastern stripped area at Thalweg occurrence in Bannockburn Township showing the irregularity of the contact between the komatiitic peridotite and the massive dacitic flows. Note that the Sudbury dike terminates at the contact with the komatiitic unit.

Volcanic and Subvolcanic Architecture

Distinguishing between extrusive and intrusive origins for komatiitic units is generally difficult because of incomplete exposure and/or deformation of contacts, and the fact that several komatiite textures (e.g., spinifex, amygdules) can occur in both extrusive and intrusive units (Arndt et al. 2004; Houlé, Lesher and Gibson 2004). On the other hand, several komatiite textures provide unequivocal evidence for an extrusive mode of emplacement, including flow-top breccia, flow breccia, hyaloclastite, and polyhedral (polysutured) jointing.

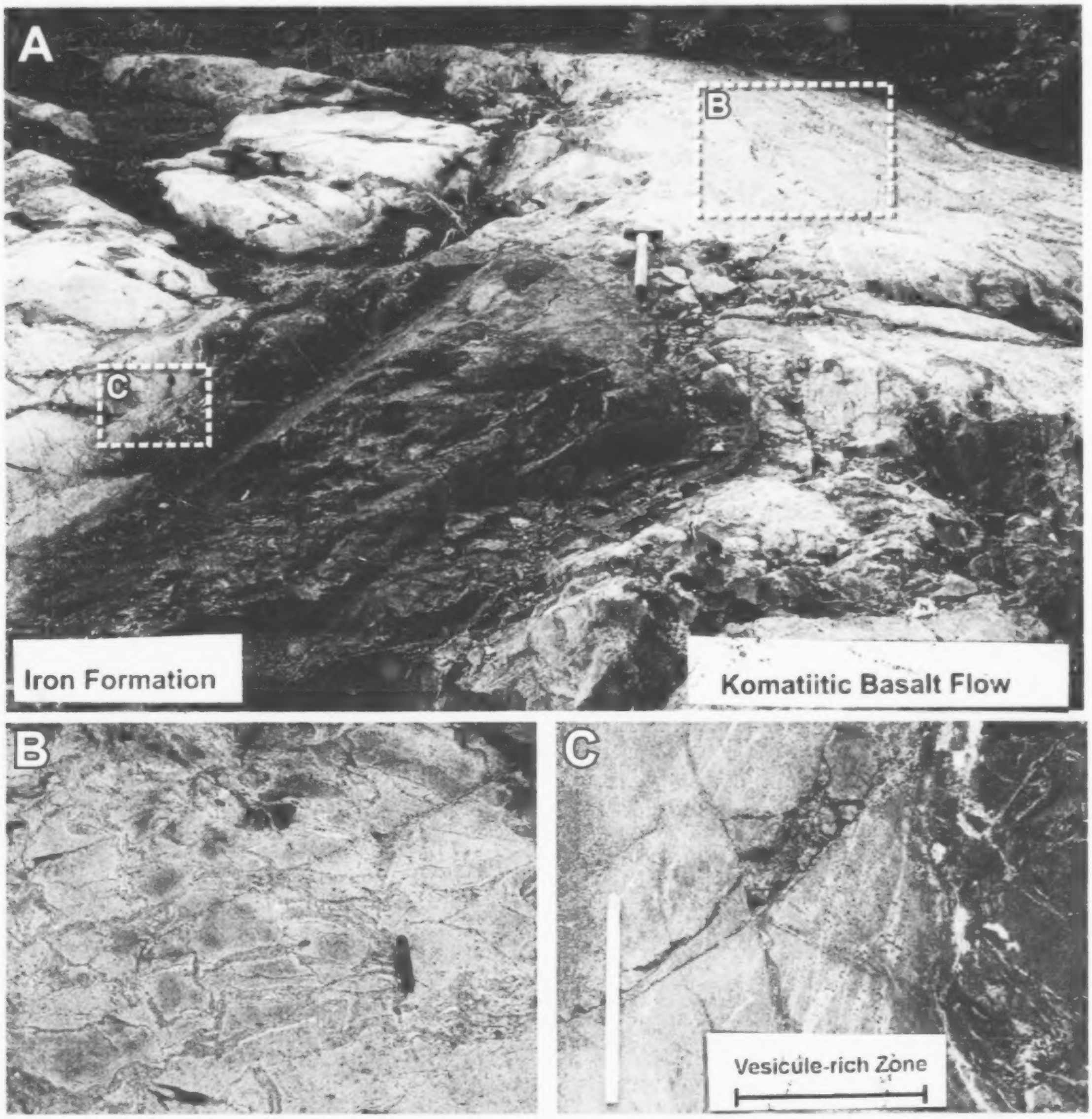


Photo 7.3. A) Iron formation xenoliths into a komatiitic basalt flow. B) Close-up from Photo 7.3A showing a jigsaw-fit *in situ* komatiitic basalt hyaloclastite. C) Close-up from Photo 7.3A showing the contact between komatiitic baslat flow and the iron formation xenolith. Note the highly vesicular zone along the contact.

In the eastern half of the map area (Powell and Cairo townships), the komatiitic units (Ban-9 to Ban-18) exhibit unequivocal evidence for extrusion such as *in situ* komatiitic hyaloclastites, flow breccias, flow-top breccias, and polysutured jointing. However, the evidence is ambiguous for the komatiitic occurrences (Ban-5 to Ban-8) in Bannockburn Township where some of the komatiitic units exhibit evidence for extrusion or intrusion. Examples include those in the northern part of the area (Ban-7D) that contain flow-top breccias or those having a high angular relationship with others units (Ban-8: C-Zone). No strong evidence either way was observed thus far about the origin of the other occurrences in Bannockburn Township. However, several factors could suggest that these units are more likely to be intrusive rather than flows including the presence of steep- and shallow-dipping units, the presence of discordant komatiitic units (C-Zone), the absence of lateral continuity (i.e., isolated blobs on the map of the magnetic survey (OGS 1999)), large amount of sulphides within small komatiitic units (C-Zone), the absence of an obvious sulphur source and the overall complexity of the geology associated with these komatiitic units. The lack of data on the komatiitic units in the western part of Montrose Township (Ban-1 to Ban-4) prohibits any interpretation on their origin (i.e., flow versus intrusion).

Interpreting volcanic environments is complicated by both primary factors (e.g., more than one eruptive centre, differences in eruption rate and style, differences in mode and environment of emplacement) and secondary factors (e.g., metamorphism, alteration, structural complexity, exposure, etc.). However, there are clear volcanic facies variations in the Bannockburn Township area. The komatiites in the west-central part of Bannockburn Township contain more prospective volcanology (e.g., cumulate rocks, less differentiated, degree of channelization, underlying lithologies) than the komatiites elsewhere in the area.

The komatiitic rocks in the Bannockburn area are tentatively interpreted to be a complex sill-lava flow field, whereas, in the west-central part of Bannockburn Township, the rocks are interpreted to be high-level komatiitic subvolcanic intrusions and feeder dikes that feed komatiitic channelized sheet flows and thin differentiated flows further east in Bannockburn and Powell townships.

KOMATIITE-ASSOCIATED NICKEL-COPPER-(PLATINUM GROUP ELEMENT) MINERALIZATION

Komatiite-hosted Ni-Cu-(PGE) deposits contain a variety of mineralization types (Lesher and Keays 2002), which may be subdivided into 3 broad genetic categories: magmatic, metamorphically hydrothermally mobilized, and tectonically mobilized. Each of these categories may be subdivided into several types and subtypes (Lesher and Keays 2002) (Table 7.2). The most favourable Ni-Cu-(PGE) primary mineralization types in the Bannockburn area are, in order of economic potential, stratiform basal (Type I: Kambalda-type), stratabound internal (Type II: Mt. Keith type), and stratiform internal (Type III: "reef-type").

Four significant nickel sulphide mineralization zones are known in the Bannockburn area from past exploration programs. The C-Zone, the Thalweg Zone (F-Zone), and the Rahn Lake Zone (D-Zone) are related to the Kambalda-type, whereas the Bannockburn (B-Zone) is related to the Mt. Keith-type (*see* Table 7.2). Other sulphide occurrences associated with komatiitic rocks in the study area include the H-Zone (0.4–0.7% Ni: unpublished data from Mustang Minerals) located northeast of Rahn Lake in Bannockburn Township, and trenches that contain disseminated sulphides (up to 25%: Benson 2005) located near the boundary between Powell and Bannockburn townships. In the following section, the most significant komatiite-associated Ni-Cu-(PGE) zones are summarized from direct observations and data available from Outokumpu Mines and Mustang Minerals.

Table 7.2. Simplified classification of *primary* mineralization types in *komatiite-associated* magmatic Ni-Cu-PGE deposits (*modified from* Lesher and Keays 2002) in the Abitibi greenstone belt.

Origin	**Type**		
Type	**I** **Stratiform Basal**	**II** **Stratabound Internal**	**III** **Stratiform "Reef-style"**
Sulphide distribution	At or near the bases of komatiitic peridotite or komatiitic dunite units	Within komatiitic peridotite or dunite units	At or near contact between lower ultramafic cumulate zones and upper mafic zones
Sulphide textures	Massive, net-textured, disseminated	Disseminated, interstitial	Disseminated
Timing and paragenesis	Segregated prior to or during emplacement	Segregated during crystallization of cumulate host rock	Segregated during final stages of crystallization of host rock
Examples in the Bannockburn area	- *C-Zone* - *Thalweg Zone (F Zone)* - *Rahn Lake Zone (D Zone)*	- *Bannockburn Zone (B Zone)*	*Unknown*

The C-Zone is the most recent discovery and is exposed over a length of 150 m (Ban-8: *see* Figure 7.1). The sulphide mineralization consists of massive sulphides and disseminated to blebby sulphides and occurs at or slightly above the contact with dacite (Photo 7.4). Rare net-textured sulphides are also observed locally. The apparent thickness of the sulphide zone on the surface ranges from 1.5 to 6 m, whereas true thickness estimated from diamond drilling ranges between 0.5 to 8 m (Harron 2005). The ore zone is generally composed of very fine-grained and highly deformed sulphides that contain numerous talc-carbonate stringers. It is composed of pyrrhotite, pentlandite, chalcopyrite, pyrite and magnetite. In some locations, the sulphide mineralization is intensely weathered and oxidized. Table 7.3 shows the typical grade of the C-Zone mineralization over the length of the stripped area. The C Offset Zone is interpreted to be the equivalent of the C-Zone sulphide lens displaced by a north-northwest- to south-southeast-trending fault.

The Thalweg nickel sulphide mineralization is located south-southwest of Charlewood Lake in the southwest corner of Bannockburn Township (Ban-5: *see* Figure 7.1). The sulphide mineralization at Thalweg is hosted within a thick komatiitic peridotite that occurs at or near the basal contact of a footwall embayment. The sulphide mineralization is continuous over 200 m and could locally be up to 18 m wide (Bereton 2003). This occurrence is typical of a Kambalda-type mineralization composed of massive sulphides, net-textured sulphides, and disseminated sulphides. Table 7.3 shows the typical grade of the Thalweg mineralization intersected by Outokumpu Mines and Mustang Minerals. Some mineralization is also reported within footwall projection along the main channel (Davis 1996).

The Bannockburn Zone (B-Zone) is located approximately 2 km north-northwest of the Thalweg Zone and approximately 200 m southwest of the C-Zone at Rahn Lake (Ban-7A: *see* Figure 7.1). The host unit of the B-Zone is an olivine adcumulate to mesocumulate trending northwest-southeast for over 3 km. The B-Zone is typical of Mt. Keith type mineralization with fine disseminated sulphides (1–3%) within a thick olivine cumulate. Table 7.3 shows the typical grade of the B-Zone mineralization intersected by Outokumpu Mines and Mustang Minerals.

The Rahn Lake Zone (D-Zone) has been intersected by diamond drilling conducted by Outokumpu Mines in the swamp at the bottom of a cliff near the C-Zone and more recently by Mustang Minerals under Rahn Lake. The sulphide zone ranges in thickness from 1 to 3 m thick and is mainly composed of disseminated to net-textured sulphides that occur at or near the basal contact of a relatively thick olivine cumulate. A narrow horizon of massive sulphides is locally observed underlying the main ore profile.

Table 7.3. Grade summary of the main nickel sulphide mineralization at the Mustang Minerals property in Bannockburn Township. Compiled *from* Bereton (2003), Harron (2005) and unpublished data from Outokumpu Mines.

Nickel Zone	Sulphide Texture	(n)	Average Ni (%)	Min Ni (%)	Max Ni (%)	Sulphides (%)
C-Zone						
Surface	D$ to B$	9	0.67	0.19	1.09	5-25
	M$	16	3.5	1.97	4.85	>90
Thalweg Zone						
	D$	21	0.39	0.14	1.06	1-10
	N$	15	1.14	0.87	2.16	15-60
	M$	3	3.42	2.5	4.54	90-97
Bannockburn Zone						
	D$	12	0.30	0.28	0.51	Tr-1%
	D$	8	0.64	0.31	0.97	2-3%
Rahn Lake						
	D$	4	0.85	0.61	1.23	5-10
	N$	2	1.19	1.16	1.21	10-40
	M$	1	3.2	–	–	90

M$: Massive sulphides, N$: Net-textured sulphides, D$: Disseminated sulphides, B$: Blebby sulphides, (n): number of analysis.

Table 7.3 shows the typical grade of the D-Zone mineralization intersected by Outokumpu Mines and Mustang Minerals. The sulphide mineralization is composed of pyrrhotite, pentlandite and pyrite. Some disseminated sulphides (3–10% pyrite, pyrrhotite) are equally present near the upper contact with the dacite that constitutes the footwall of the C-Zone. Other fine disseminated sulphides were intersected within the D-Zone by diamond drilling under Rahn Lake. However, in accordance with the new structural interpretation, this sulphide zone may be related to the B-Zone rather than the D-Zone.

MINERAL POTENTIAL EXPLORATION

Komatiite-associated Ni-Cu-(PGE) deposits typically occur in clusters. For example, within the Abitibi greenstone belt, there are the following deposits: in the Shaw Dome, there are 5 known deposits (Langmuir #2, Redstone, Langmuir#1, McWatters, Hart); in the Dundonald area, there are 4 known deposits (Alexo, Kelex, Dundonald South, Dundeal); and in the Lamotte area in Québec, there are at least 4 deposits (Marbridge 1, 2, 3, 4: Naldrett and Gasparrini 1971). This is also typical for komatiite-associated Ni-Cu-(PGE) deposits worldwide, as exemplified by the deposits in the Kambalda–St Ives–Tramways–Widgoemooltha–Carnilya Hill district of Western Australia (Barnes 2004). Clearly, areas where only one or two deposits have been discovered, such as the Bannockburn area, have significant potential for discovery of additional deposits.

Several factors appear to be critical to the genesis of economically significant magmatic sulphide deposits (e.g., Lesher and Keays 2002; Naldrett 2004), including

1. **Source of Metal**: The magma must be initially undersaturated in sulphide so that it contains sufficient concentrations of Ni, Cu, and PGE;
2. **Source of S**: The magma must have access to an external sulphur source to achieve early sulphide saturation and to segregate significant abundances of immiscible sulphides at a high (crustal) level;

3. **Dynamic System**: The ores must form in a dynamic system where the magmas can interact with country rocks (to extract S) and where the sulphides can equilibrate with a sufficient amount of magma to generate high chalcophile element contents in the sulphides (i.e., high R factor);
4. **Physical Trap**: The sulphides must be concentrated in some type of physical trap (embayment, inflection).

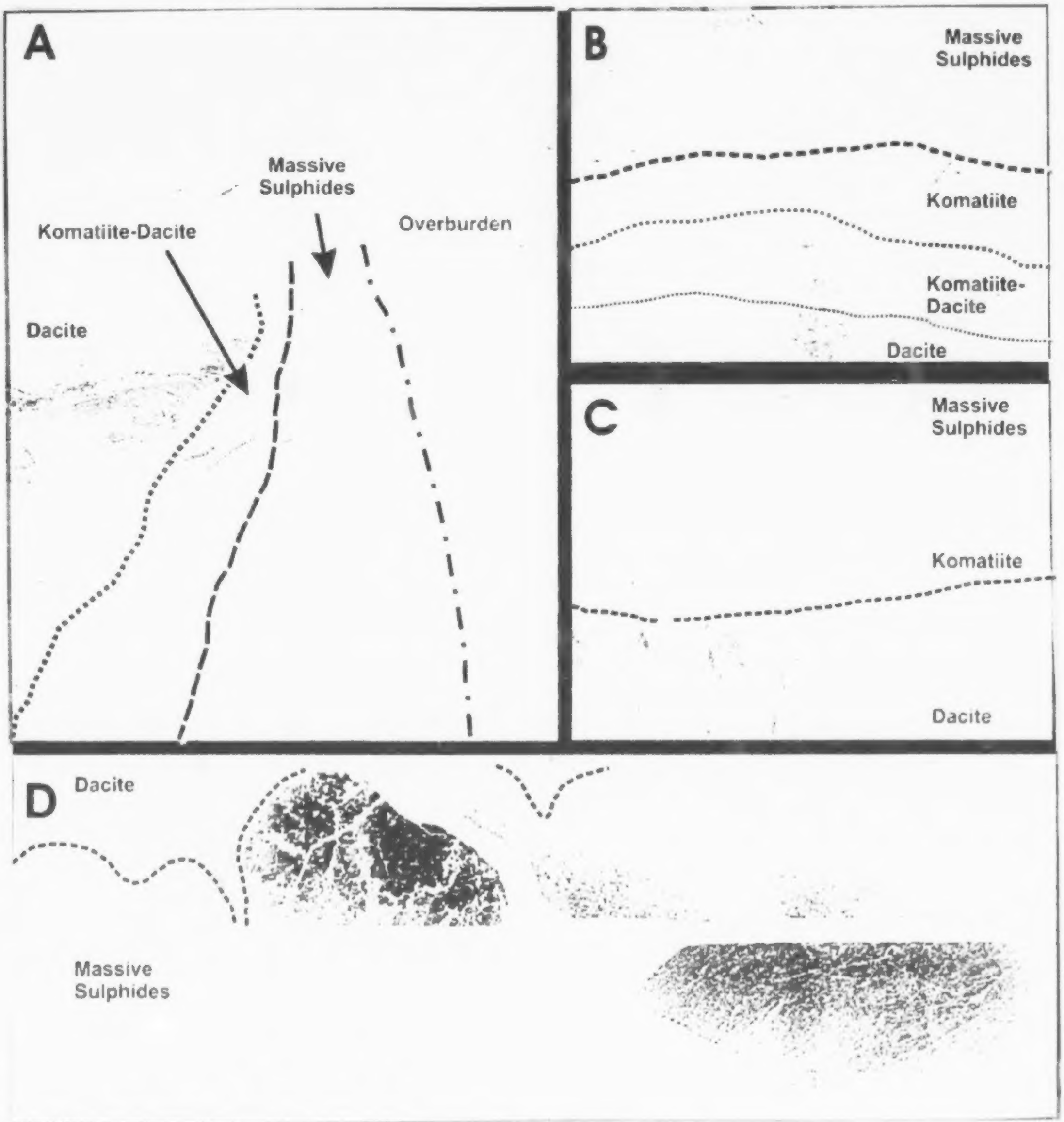

A
Massive Sulphides
Komatiite-Dacite
Overburden
Dacite
B
Massive Sulphides
Komatiite
Komatiite-Dacite
Dacite
C
Massive Sulphides
Komatiite
Dacite
D
Dacite
Massive Sulphides

Photo 7.4. Nickel sulphide mineralization at the C-Zone in Bannockburn Township. A) The C-Zone mineralization exposed on the eastern edge of the stripped area (looking east) showing the footwall contact between massive sulphide, komatiite and dacite. B) Close-up from Photo 7.4A showing the interaction between komatiite and overlying massive sulphides and underlying plagioclase-phyric dacite. C) Footwall contact further up on the hill showing a sharp contact between komatiite and dacite underlying massive sulphides indicating little to no interaction between those units. D) Footwall contact from diamond drill core (MBC04-12) showing very irregular contact between dacite and massive sulphide.

Numerous occurrences of nickel, copper and platinum group element mineralization associated with komatiitic rocks have been identified in the Bannockburn area (C-Zone/C Offset, B-Zone, F-Zone, H-Zone). Furthermore, Sproule et al. (in press) concluded that all of the host rocks were undersaturated in sulphide prior to emplacement in the Abitibi greenstone belt, including the Bannockburn area komatiites, suggesting that those rocks originally contain sufficient concentrations of metals. The presence of relatively thick olivine cumulate (within several komatiite occurrences: Ban-07, Ban-05, and Ban-06), and of numerous autobrecciated units (within the Rahn Lake and C-Zone komatiites), suggest a high dynamic system for the komatiitic rocks. The presence of embayments and the interaction between the intermediate volcanics rocks and the komatiite units at the C-Zone and the Thalweg stripped exposures suggest contamination and localized physical traps to accumulate sulphide mineralization. As noted above, these features are all critical in the formation of magmatic Ni-Cu-(PGE) mineralization.

The recent work conducted by the Ontario Geological Survey (Préfontaine and Berger, this volume; Berger and Préfontaine, this volume) in this area increases significantly the understanding of the regional geological context. The new structural interpretation suggests that most of the komatiitic units in the Bannockburn area are part of the same komatiitic sequence. Incidentally, this highlights some important implications on the potential of this area for nickel mineralization. Firstly, the presence of northwest to southeast folding in this area is indicated by reversals in stratigraphic facing and this suggests that komatiites and associated mineralization may be repeated by folding. Furthermore, structural repetition of the komatiite stratigraphy suggesting that the two komatiitic units north of the known occurrences are probably underexplored for their Ni-Cu-(PGE) potential. Secondly, without clear knowledge of the facing of a particular unit, past diamond drilling may have been drilled down dip and/or may not have tested the basal contacts of the komatiites for potential mineralization.

Identification of three compound sheets flows in the map (Ban-11, Ban-15 and Ban-17) that could contain lava pathways should be further investigated for nickel potential. The komatiite occurrence Ban-11 contains a fair amount of sulphides within its flanking facies suggesting the presence of a sulphur source in the immediate vicinity.

Several high gravity anomalies occur in the map area (OGS 1999). Most of these appear to be related to high-density rocks such as komatiite and iron tholeiite. One good example is the high gravity anomaly located in central Powell Township that appears to be associated with the most extensive komatiitic flows in the map area. However, contrary to the komatiite flows in central Powell Township, no high gravity anomaly is associated with those high-level komatiite intrusions. An unexplained gravity anomaly is situated east of Charlewood Lake and Clarke Lake under rocks of the Gowganda Formation. It occurs south-southeast of the komatiite occurrence Ban-07 (C-Zone, Bannockburn Zone, Rahn Lake) and north-northwest of the komatiite occurrence Ban-05 (Thalweg area). This anomaly may be related to ultramafic rocks and presents an attractive exploration target for magmatic sulphide mineralization.

Despite the lack of obvious sulphur sources in the area, the combination of a fertile komatiitic magma (metal source), abundant olivine cumulate rocks indicating high magma flux (heat source and dynamic environment), a clear interaction (contamination via thermomechanical erosion) between the komatiitic units and their footwall (dynamic environment), and embayments (localization) provides an excellent environment for forming komatiite-associated Ni-Cu-(PGE) deposits in the study area.

ACKNOWLEDGMENTS

This contribution has been designed to complement the regional bedrock mapping, which is part of the Ontario Geological Survey core program and is part of an ongoing PhD study by M.G. Houlé based at Laurentian University (LU) and the University of Ottawa (UO) on the physical volcanology and metallogenesis of komatiites in the Abitibi greenstone belt. Peter Wood and Ken Lapierre from Mustang

Minerals Corp. are thanked for their generous assistance, numerous discussions and permission to access properties and internal company data. Insightful discussions and comments from other geoscientists such as Rebecca Sproule, Mike Lesher, and Harold Gibson from Laurentian University and Paul Davis from First Nickel Inc. were greatly appreciated.

REFERENCES

Arndt, N.T., Lesher, C.M., Houlé, M.G., Lewin, E. and Lacaze, Y. 2004. Intrusion and crystallization of a spinifex-textured komatiite sill in Dundonald Township, Ontario: Journal of Petrology, v.45, p.2555-2571.

Ayer, J.A., Thurston ,P.C., Bateman, R., Dubé, B., Gibson, H.L., Hamilton, M.A., Hathway, B., Hocker, S.M., Houlé, M.G., Hudak, G., Ispolatov, V.O., Lafrance, B., Lesher, C.M., MacDonald, P.J., Péloquin, A.S., Piercey, S.J., Reed, L.E. and Thompson, P.H. 2005. Overview of results from the Greenstone Architecture Project: Discover Abitibi Initiative; Geological Survey, Open File Report 6154, 146p.

Barnes, S.J. 2004. Introduction to nickel sulfide orebodies and komatiite of the Black Swan area, Yilgarn Craton, Western Australia; Mineralium Deposita, v.39, p.679-683.

Benson, D. 2005. Report on the 2004 summer mapping and sampling program on the Powell Property, Powell and Bannockburn townships, Ontario for Mustang Minerals Corp.; Kirkland Lake Resident Geologist office, assessment file # KL-5415.

Bereton, W.E. 2003. Report on the Bannockburn Nickel Property, Bannockburn, Matachewan area, Ontario for Mustang Minerals Corp.; NI43-101 compliant, unpublished report, MPH Consulting Limited, 59p.

Berger, B.R. and Leblanc, G. 2002. Geology of Cairo Township, District of Timiskaming; *in* Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.8-1 to 8-7.

Davis, P.C. 1996. Thalweg Nickel Showing, Bannockburn Property; unpublished report, Outokumpu Mines Ltd., 13p., including 5 appendices.

Harron, G.A. 2005. Technical report on Bannockburn Nickel Property, Bannockburn, Doon, Montrose, Hincks and Zavitz townships, Ontario for Mustang Minerals Corp., NI43-101 compliant, MPH Consulting Limited, 50p.

Houlé, M.G., Lesher, C.M. and Gibson, H.L. 2004. The significance of spinifex textures in constraining the volcanic settings of precambrian komatiitic and ferropicritic rocks: the Boston Creek sill; abstract, Geological Association of Canada–Mineralogical Association of Canada, Annual Meeting, St. Catharines, Ontario, Program with Abstracts, v.29, p.417.

Leblanc, G. and Berger, B.R. 2003. Precambrian geology, Cairo Township; Ontario Geological Survey, Preliminary Map P.3522, scale 1:20 000.

Lesher, C.M. and Keays, R.R. 2002. Komatiite-associated Ni-Cu-PGE deposits: geology, mineralogy, geochemistry and genesis; *in* The geology, geochemistry, mineralogy and mineral beneficiation of platinum-group elements, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, p.579-618.

Naldrett, A.J. 2004. Magmatic sulfide deposits: geology, geochemistry and exploration; Springer-Verglag, Berlin, 727p.

Naldrett, A.J. and Gasparrini, E.L. 1971. Archean nickel sulphide deposits in Canad their classification, geological setting and genesis with some suggestions as to exploration; Geological Society of Australia, Special Publication 3, p.201-226.

Ontario Geological Survey 1999. Single master gravity and aeromagnetic data for Ontario; Ontario Geological Survey, ERLIS Data Set 1036.

Sproule, R.A., Lesher, C.M., Houlé, M.G., Keays, R.R., Ayer, J.A. and Thurston, P.C. *in press*. Chalcophile element geochemistry and metallogenesis of komatiitic rocks in the Abitibi greenstone belt, Canada: Economic Geology.

8. Project Unit 03-002. Synthesis of Archean Geology and Diamond-bearing Rocks in the Michipicoten Greenstone Belt: Results from Microdiamond Extraction and Geochronological Analyses

C. Vaillancourt[1], J.A. Ayer[1] and M.A. Hamilton[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Jack Satterly Geochronology Laboratory, Department of Geology, University of Toronto, Toronto, Ontario

INTRODUCTION

Diamonds were first discovered *in situ* in an Archean-age dike at the Sandor locality in the Michipicoten greenstone belt of the eastern Wawa Subprovince in 1996 (Sage 2000). The Michipicoten greenstone belt contains sequences of volcanism consisting of combinations of komatiitic, tholeiitic and calc alkaline rock types. The three volcanic assemblages defined by Williams et al. (1991) are the Hawk, Wawa and Catfish assemblages, which correspond to volcanic cycles 1, 2 and 3 described by Sage (1994), and have approximate ages of 2900 Ma, 2750 Ma, and 2700 Ma (Sage 1994).

This project was initiated in 2003 in response to the numerous diamond discoveries in Archean breccias and lamprophyres near Wawa, Ontario. To date, bedrock geology mapping resulted in the publication of a 1:20 000 scale map of Menzies Township (Vaillancourt, Dessureau and Zubowski 2005) and a Miscellaneous Release—Data (Vaillancourt, Zubowski and Dessureau 2005), which contains lithogeochemical analyses of samples from Menzies and Musquash townships, and accompanying photographs. Details of the regional geology including references to previous work in the area can be found in Vaillancourt, Wilson and Dessureau (2003) and Vaillancourt et al. (2004).

The purpose of this article is to report the results of microdiamond extraction carried on three bedrock samples from Menzies and Musquash townships, and the results of new geochronological analyses from a sample in Menzies Township.

MICRODIAMOND EXTRACTION

Sample Preparation and Analytical Process

Prior to submission for analyses, each of the three samples was reduced to fist-size pieces, which were carefully brushed and rinsed thoroughly to avoid any potential contamination by Quaternary deposits. The samples were submitted to SGS Lakefield Research Limited for microdiamond extraction, selection and description. Caustic dissolution residues were collected on a 100 µm screen and submitted for Frantz™ magnetic separation to isolate the microdiamonds in the non-paramagnetic fraction.

Summary of Field Work and Other Activities 2005
Ontario Geological Survey, Open File Report 6172, p.8-1 to 8-13

© Queen's Printer for Ontario, 2005

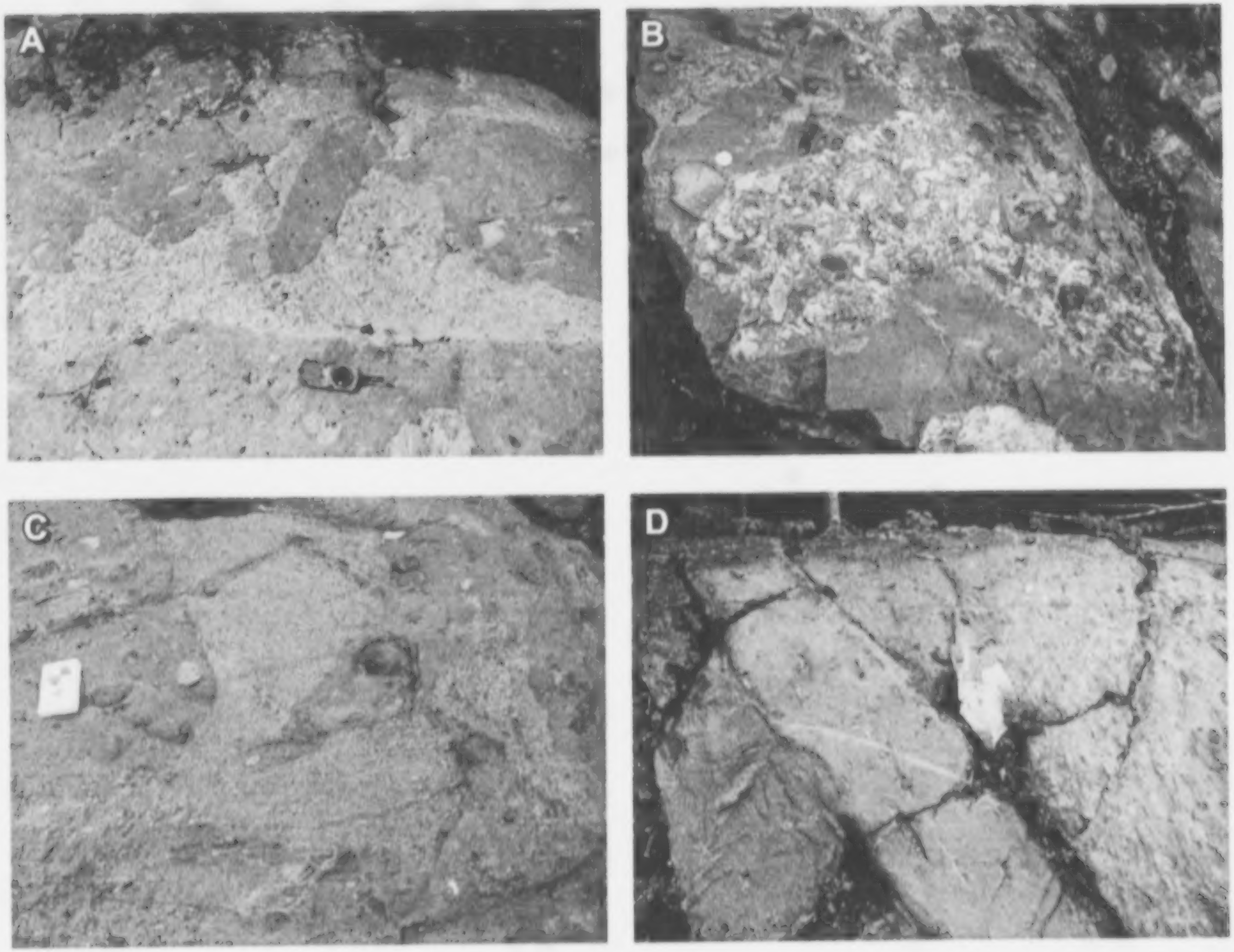


Photo 8.1. Relationships between different types of heterolithic breccias and lamprophyres. A) Crystal occurrence, Pele Mountain Resources Inc.; B) Wawa Diamond Project, Spider Resources Inc. and KWG Resources Inc.; C) Genesis occurrence, Pele Mountain Resources Inc.; and D) Genesis occurrence, Pele Mountain Resources Inc.

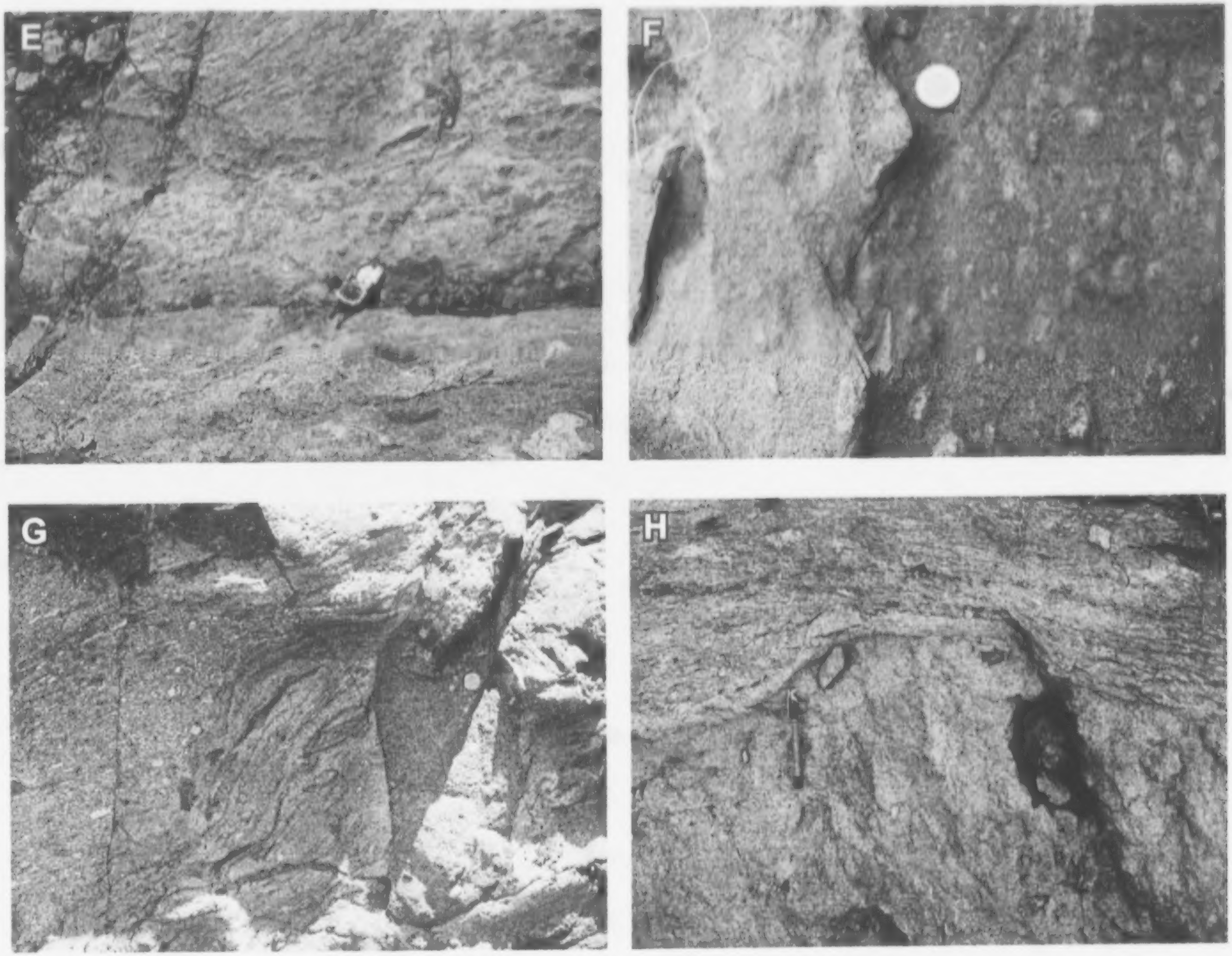


Photo 8.1 (cont.). E) Mumm occurrence, Pele Mountain Resources Inc.; F) Wawa Diamond Project, Spider Resources Inc. and KWG Resources Inc.; G) Enigma property, Oasis Resources Inc.; and H) Genesis occurrence, Pele Mountain Resources Inc.

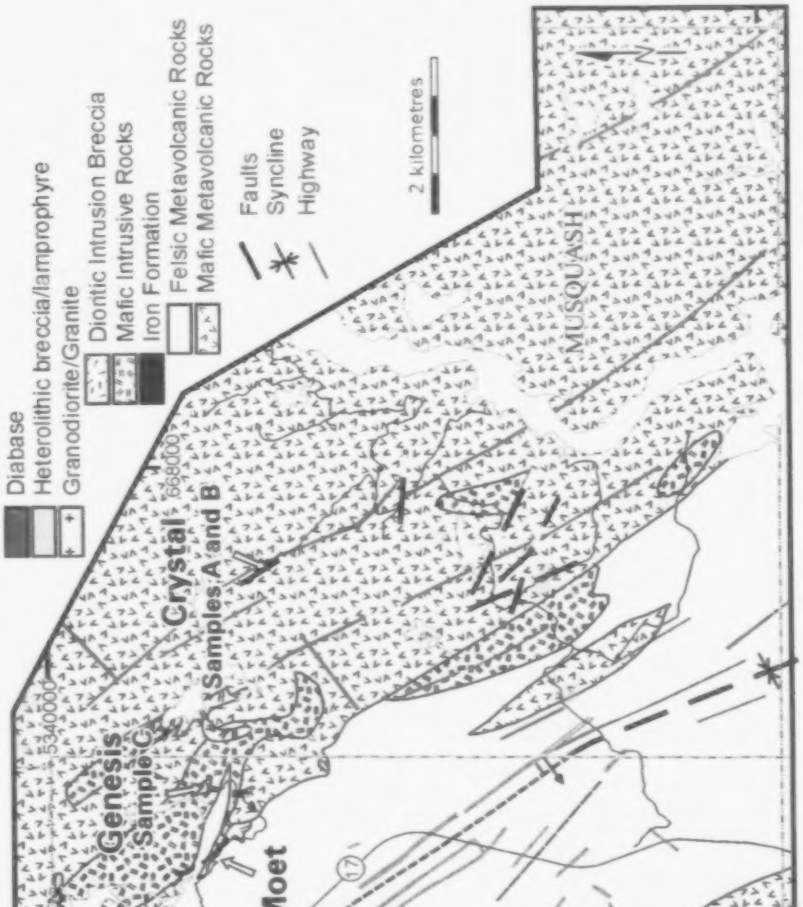

Diabase
Heterolithic breccia/lamprophyre
Granodiorite/Granite
Dioritic Intrusion Breccia
Mafic Intrusive Rocks
Iron Formation
Felsic Metavolcanic Rocks
Mafic Metavolcanic Rocks
Faults
Syncline
Highway
2 kilometres
N
LALIBERT
MENZIES
MUSQUASH
Genesis
Sample C
Crystal
Samples A and B
Moet
Sample D
17
5340000
5331000
655000
668000

Figure 8.1. General geology of Menzies and Musquash townships. Geology of Menzies Township is from Vaillancourt et al. (2004). Geology of Musquash Township is a representation at a larger scale and does not include the details of the diamond-bearing units. Letters A to C are locations for samples submitted for microdiamond analyses and D is the location of the sample submitted for geochronological study as discussed in text.

Table 8.1. Description of samples processed for microdiamond extraction by caustic dissolution.

Sample	UTM Co-ordinates (NAD83)		Weight (kg)	Description
	Easting (m)	Northing (m)		
A	666464	5337318	31.60	Heterolithic breccia with ultramafic "pockets"
B	666500	5337330	32.13	Heterolithic breccia
C	663644	5338062	31.48	Ultramafic dike

Rationale for Microdiamond Analyses

A number of diamond occurrences were investigated during the mapping of Menzies and Musquash townships. All of the occurrences that were studied show a complex interaction between a number of different rock units. Each occurrence typically includes a variety of heterolithic breccias with different fragment size or ratios of matrix to fragments, and/or lamprophyric dikes with different fragment content and matrix compositions. Photos 8.1A and 8.1B show an ambiguous relationship between a fragment-supported breccia, which either intrudes or fills gaps in between a fragmented chlorite-rich matrix-supported breccia. Photo 8.1C shows a similar relationship between a small fragment-supported breccia and a biotite-rich matrix-supported breccia with larger fragments. A lamprophyric dike cuts across a fragment-supported breccia (right) and its host gabbro (left) on Photo 8.1D. A small dike of fragment-supported breccia with a large proportion of dark fragments cuts across a biotite-rich matrix-supported breccia or lamprophyre on Photo 8.1E. There is a reaction rim between the dike and its host. A green biotite-rich lamprophyric rock (left) is in contact with a brown biotite-rich lamprophyric rock (right) on Photo 8.1F. Note that the actinolite-rich fragments are restricted to the chlorite-rich units. The relationship between the small fragment-supported (left) and matrix-supported (centre) breccias is ambiguous on Photo 8.1G. Also note, the lamprophyric looking possible fragment with wispy edges on the right of the photograph. Finally, Photo 8.1H shows a contact between two fragment-supported breccias with fragments in different amounts, and of different sizes and nature.

A closer look at the locations where the bulk samples were taken for diamond extractions by the exploration companies suggests that the samples likely included more than one rock unit. It was, therefore, difficult to assess which rock unit carried diamonds and, more specifically, where the diamonds were located within the units (i.e., matrix versus a specific fragment type). The presence of ultramafic dikes proximal to all areas where Pele Mountain Resources obtained the largest diamonds (0.7 carat at Crystal and 0.9 carat at Genesis occurrences) stimulated our interest in investigating these dikes in more detail. Therefore, three small samples were submitted for microdiamond extraction in an attempt to better understand the specific location(s) of the diamonds. Sample locations are shown in Figure 8.1 and details are presented in Table 8.1. The samples are from the Crystal and Genesis occurrences, both of which are located on the Festival Property, currently held by Pele Mountain Resources Inc.

Sample Descriptions

At the Crystal occurrence, the ultramafic dikes clearly cut across the mafic pillowed flows, brecciating their host (Photo 8.2). These are small in width and difficult to sample for diamond analysis. The presence of ultramafic magma "pockets" was noted in a heterolithic breccia located a few metres from the location where dikes cut the pillowed flows. This breccia (sample A) was sampled for microdiamond analysis (Photo 8.3). A similar breccia without the ultramafic pockets (Sample B; Photo 8.4) was also sampled for comparison purpose. Finally, a large ultramafic dike without any fragments (Sample C; Photo 8.5) was sampled at the Genesis occurrence site.

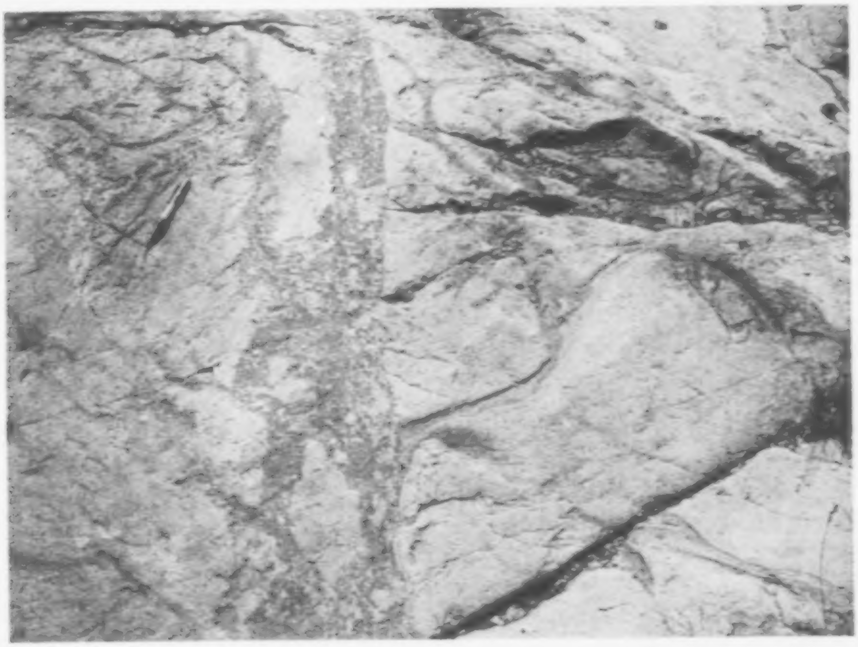


Photo 8.2. Ultramafic dike cutting and brecciating mafic pillowed flow. Crystal occurrence, Musquash Township.

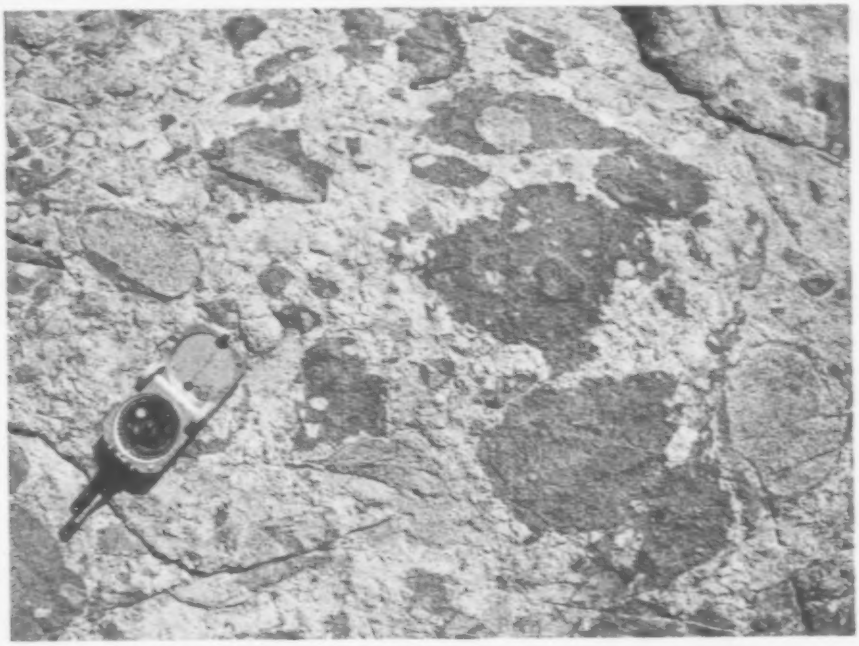


Photo 8.3. Fragment supported heterolithic breccia with ultramafic magma "pockets". Crystal occurrence, Musquash Township. Photograph taken at location of sample A.

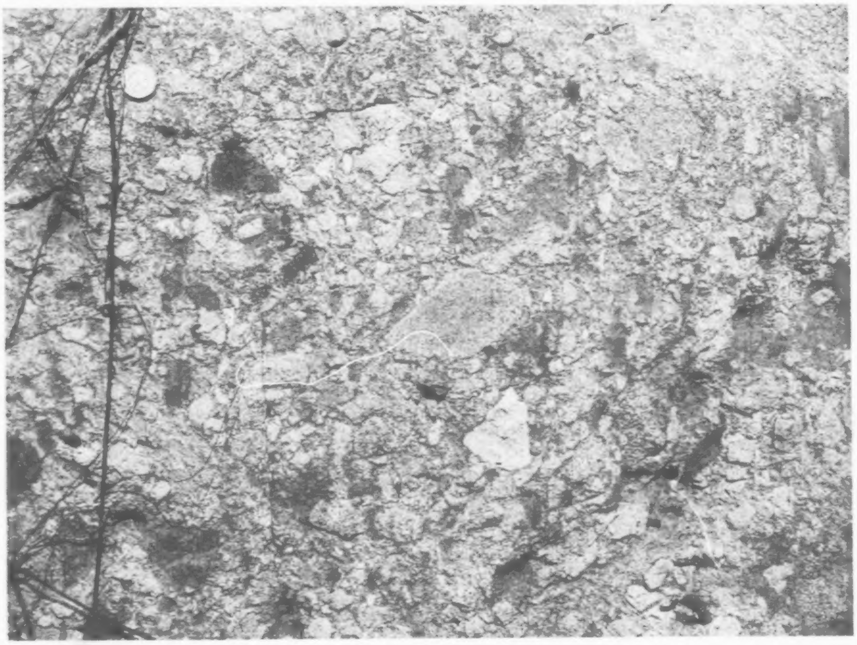


Photo 8.4. Fragment supported heterolithic breccia, Crystal occurrence, Musquash Township. Photograph taken at location of sample B.

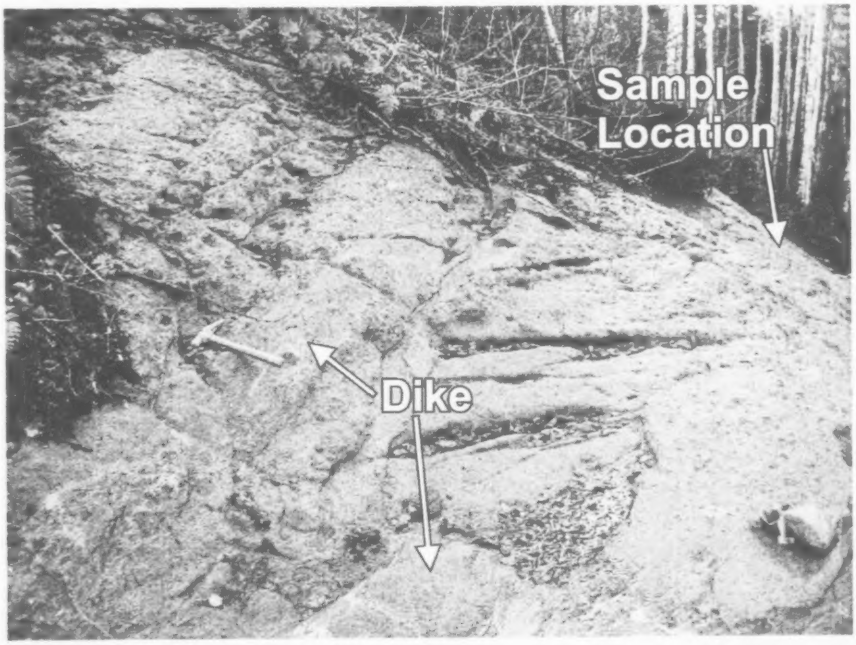


Photo 8.5. Ultramafic dike cutting heterolithic breccia, Genesis occurrence, Menzies Township. Photograph taken at location of sample C.

Table 8.2. Results of microdiamond extraction by caustic dissolution.

Diamond Size Fractions	Number of Stones in A	Number of Stones in B	Number of Stones in C
+4.75 mm	0	0	0
–4.75 / + 3.35 mm	0	0	0
–3.35 / + 2.26 mm	0	0	0
–2.36 / + 1.70 mm	0	0	0
–1.70 / + 1.18 mm	0	0	0
–1.18 / + .85 mm	0	0	0
–850 / + 600 μm	0	0	1
–600 / + 425 μm	0	0	1
–425 / + 300 μm	0	0	1
–300 / + 212 μm	0	10	0
–212 / + 150 μm	1	23	2
–150 / + 105 μm	3	36	0
Total	4	69	5

Sample A is a fragment-supported heterolithic breccia. The most abundant fragment types are locally derived mafic and felsic volcanic and gabbroic rocks fragments. Other types, which are not known to occur locally, include talc-rich fragments with chromium-rich chlorite phenocrysts and rare but typically large pyroxenite fragments. This breccia contains "pockets" of amphibole-porphyritic ultramafic rock which may have crystallized from magma injections. These "pockets" have irregular shapes of different sizes and typically include one or more fragments (*see* Photo 8.3). In thin sections, this fraction is observed to have a porphyritic texture composed of large crystals of hornblende, epidote and chlorite with minor carbonates, in a matrix of fine amphibole, feldspar and epidote.

Sample B is also a fragment-supported breccia, which contains the same fragments as Sample A, with the addition of rusty biotite-rich fragments (*see* Photo 8.4). In thin section, these fragments have a remnant subophitic texture formed by plagioclase laths surrounded by actinolite , which is partially replaced by biotite. These fragments also contain minor carbonate. This breccia is free of the magma "pockets".

Sample C is a totally recrystallized fine-grain ultramafic rock (*see* Photo 8.5). It is composed of oriented actinolite, wormy epidote and very minor chlorite.

Results

A summary of the results for microdiamond extraction by caustic dissolution for the three samples are presented in Table 8.2. Details on each diamond are presented in Appendix 8.1.

Discussion

Based on the count and size of microdiamonds obtained for the three samples, a number of conclusions can be drawn. However, results obtained on only three samples may be fortuitous and interpretations should be regarded as preliminary. Previous analyses done by different exploration companies in the past have suggested that microdiamonds are not restricted to a single unit. The results presented in this article reinforce this suggestion because microdiamonds were obtained from heterolithic breccia both with and without the ultramafic magma pockets, and from a fragment-free ultramafic dike. It is, however, possible that the microdiamonds contained in this dike are xenocrysts that were derived from diamond-bearing host rock breccias. The rationale for sampling breccias both with and without the magma "pockets" was mainly to determine if the diamonds were located in these "magma pockets". Because there was a significantly lower count of microdiamonds in the breccia with "magma "pockets", it appears that they are not significant hosts to the diamonds. The largest stones were recovered from the ultramafic dike at the Genesis occurrence. However, a significantly larger number of samples of the dikes and breccias would be required to draw statistically significant conclusions about the presence of larger stones in the dikes.

Recommendations

Because the counts of microdiamonds are generally very high in the diamond-bearing breccia, it is justified to analyze small samples, which allows the testing a variety of units at a relatively low cost. Obviously, only three samples are insufficient to draw irrefutable conclusions regarding the location of the microdiamonds. However, it is hoped that more very well constrained samples will be analyzed in the coming years, with the goal of identifying which component(s) of the diamond-bearing rock(s) is(are) the most important host(s). This understanding would provide a valuable tool to better target diamond exploration work in the area.

GEOCHRONOLOGY

Uranium-lead zircon geochronological work has been ongoing as part of this project to help better understand the nature and timing of the diamondiferous units and their host rocks within the Michipicoten greenstone belt. ^{207}Pb/^{206}Pb results to date include an age of 2701.4±2.1 Ma from a felsic volcanic horizon hosting diamondiferous units and maximum ages of 2685.0±1.0 Ma and 2684.9±1.4 Ma for diamondiferous lamprophyre dikes cutting the Catfish assemblage felsic to intermediate volcanic units in Lalibert and Menzies townships (Ayer et al. 2003). A second sample of felsic lapilli tuff adjacent to the Moet occurrence in northeastern Menzies Township (*see* Figure 8.1) contains zircons that returned a Catfish assemblage age of 2698.7±1.1 Ma (Vaillancourt et al. 2004).

Lamprophrye dikes cut the diamondiferous breccias and, thus, are at least slightly younger than the breccias. In order to test the age of brecciation, a sample of diamondiferous breccia from the Moet showing was collected for geochronology. Five zircons were analyzed and concordant data was obtained for each of them. The three oldest ages are 2687±2 Ma, 2683±2 Ma and 2681±2 Ma. The two youngest zircons from this sample give data that precisely overlap each other at 2679.2±2.1 Ma (Vaillancourt et al. 2004). This is the youngest zircon age obtained from the breccia and, therefore, represents either the time of crystallization or emplacement of the body, providing the zircons are magmatic, or a maximum time of emplacement if the zircons are xenocrystic. In the latter case, this age must still be close to the time of breccia emplacement given that a lamprophyre dike in Musquash Township has an emplacement age of 2674±8 Ma (U/Pb age), based on a titanite analysis (Stott et al. 2002).

The data indicate that felsic volcanic units hosting the diamondiferous rocks are part of the Catfish assemblage. The maximum age for the diamondiferous breccias and the associated dikes is well established at less than 2680 Ma. Collectively, these absolute age constraints indicate that the breccias are not volcaniclastic units belonging to the Catfish assemblage (cf. Lefebvre, Kopylova and Kivi 2005). Alternatively, the age data, supported by crosscutting field relationships, suggest they are related to a diatreme brecciation event in which mantle-derived diamonds were transported into the upper crust (Wyman et al. in press). These lamprophyre and breccia ages are broadly similar to an age of 2673±8 Ma obtained for the nearby Dickenson Lake syenite stock by Turek, Sage and Van Schmus (1992).

In order to further test the ages of stratigraphic units within the Michipicoten greenstone belt, a sample of felsic lapilli tuff (03JAA-0005) was selected for analysis in northwestern Menzies Township (Figure 8.1, sample D). Heavy mineral recovery from this sample yielded an abundant quantity of zircon. The least paramagnetic population of zircon is dominated by short, somewhat irregular prisms showing sharp to slightly rounded crystal facets. A subordinate population of long (ca. 5:1) slender, colourless prisms is also present, as are occasional large fragments. Rare core-overgrowth relationships are visible in some larger grains, but these were avoided in the current geochronological study. Representative, faceted short prisms were selected for air abrasion and isotopic analysis. Results for three clear and colourless single grains are plotted graphically in Figure 8.2. All three analyses have overlapping ^{207}Pb/^{206}Pb ratios with ages ranging from 2735.5 to 2736.8 Ma and are either concordant or slightly discordant (0.1–0.6%). A weighted mean age for all three fractions is 2736.0±0.8 Ma (46% probability of fit; MSWD = 0.78), which is taken to represent the age of eruption and crystallization of the tuff.

This new age now clearly indicates that the volcanic package underlying the iron formation unit in the western part of Menzies is part of the Wawa assemblage (i.e., cycle 2) and brackets the uppermost part of this assemblage at 2736 Ma. This age is more precise than a previously analyzed Wawa assemblage ("cycle 2") felsic volcanic sample with an age of 2746±11 Ma and a quartz porphyry sample with an age of the 2742±6 Ma in the portion of the Wawa assemblage immediately overlying the circa 2.90 Ga Hawk assemblage (cycle 1) east of Wawa (Turek, Sage and Van Schmus 1992).

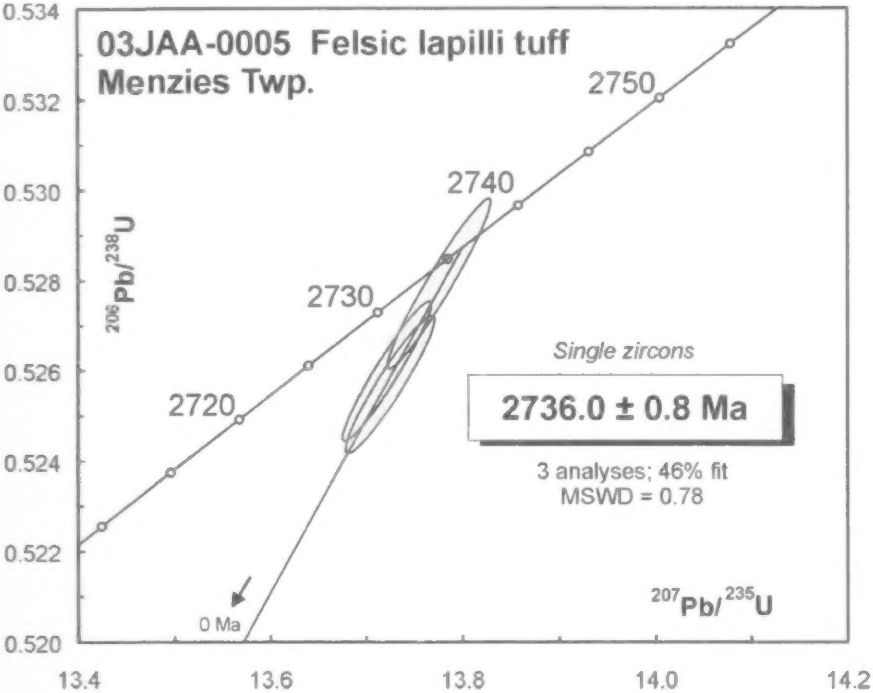


Figure 8.2. Concordia plot with U/Pb analyses of zircons from a felsic lapilli tuff sample from Menzies Township.

REFERENCES

Ayer, J.A., Conceição, R.V., Ketchum, J.W.F., Sage, R.P., Semenyna, L. and Wyman, D.A. 2003. The timing and petrogenesis of diamondiferous lamprophyres in the Michipicoten and Abitibi greenstone belts; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.10-1 to 10-9.

Lefebvre, N., Kopylova, M. and Kivi, K. 2005. Archean calc-alkaline lampyrophres of Wawa, Ontario, Canada: Unconventional diamoniferous volcaniclastic rocks; Precambrian Research, v.138, p.57-87.

Sage, R.P. 1994. Geology of the Michipicoten greenstone belt; Ontario Geological Survey, Open File Report 5888, 435p.

——— 2000. The "Sandor" diamond occurrence, Michipicoten greenstone belt, Wawa, Ontario: a preliminary study; Ontario Geological Survey, Open File Report 6016, 49p.

Stott, G.M., Ayer, J.A., Wilson, A.C. and Grabowski, G.P.B. 2002. Are the Neoarchean diamond-bearing breccias in the Wawa area related to late-orogenic alkalic and "sanukitoid" intrusions?; Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.9-1 to 9-10.

Turek, A., Sage, R.P. and Van Schmus, W.R. 1992. Advances in the U–Pb zircon geochronology of the Michipicoten greenstone belt, Superior Province, Ontario; Canadian Journal of Earth Sciences, v.29, p.1154-1165.

Vaillancourt, C., Ayer, J.A., Zubowski, S.M. and Kamo, S.L. 2004. Synthesis and timing of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt: Menzies and Musquash townships; *in* Smmary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.6-1 to 6-9.

Vaillancourt, C., Dessureau, G.R. and Zubowski, S.M. 2005. Precambrian geology of Menzies Township; Ontario Geological Survey, Preliminary Map P.3366, scale 1:20 000.

Vaillancourt, C., Wilson, A.C. and Dessureau, G.R. 2003. Synthesis of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt: geology of Menzies Township; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.9-1 to 9-11.

Vaillancourt, C., Zubowski, S.M. and Dessureau, G.R. 2005. Lithogeochemical data and field photographs for the Wawa area: Menzies and Musquash townships; Ontario Geological Survey, Miscellaneous Release—Data 151.

Williams, H.R., Stott, G.M., Heather, K.B., Muir, T.L. and Sage, R.P. 1991. Wawa Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.485-539.

Wyman, D.A., Ayer, J.A., Conceição, R.V. and Sage, R.P., in press. Mantle processes in an Archean orogen: evidence from 2.67 Ga diamond-bearing lamprophyres and xenoliths, Lithos.

Appendix 8.1. Description of microdiamonds extracted by caustic dissolution.

Sample	Fraction	Stone Dimension (mm)			Weight		Colour	Clarity	Percent Preserv.	Stone Description
		X	Y	Z	(mg)	(Carats)				Morphology
A	-850/+600 µm	0.8265	0.7980	0.38	0.293	0.001465	White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, minor cleavages, graphite inclusions
				Subtotal	0.293	0.001465				
	-600/+425 µm	0.5700	0.5130	0.42			Grey	Opaque	85%	Cubic, partially distorted, frosted
				Subtotal	0.215	0.001075				
	-425/+300 µm	0.6840	0.3990	0.37			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, significant cleavages
				Subtotal	0.101	0.000505				
	-212/+150 µm	0.3420	0.3135	0.14			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, minor cleavages, graphite inclusions
		0.2280	0.1995	0.12			White	Transparent	99+%	Octahedral
				Subtotal	0.032	0.00016				
B	-212/+150 µm	0.2850	0.2850	0.18			Green	Opaque	99+%	Cubic surface fragment
				Subtotal	0.021	0.000105				
	-150/+105 µm	0.1710	0.1425	0.11			White	Translucent	85%	Octahedral
		0.1140	0.1140	0.11			Off White	Opaque	62.5%	Dodecahedral
		0.1425	0.1140	0.08			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages
				Subtotal	0.019	0.000095				
C	-300/+212 µm	0.4845	0.3990	0.15			Off White	Transparent	99+%	Macle, twinned
		0.3705	0.3420	0.23			White	Translucent	85%	Octahedral, twinned, graphite inclusions
		0.3420	0.2850	0.24			White	Translucent	85%	Cubic, partially distorted
		0.3135	0.2565	0.24			White	Translucent	85%	Cubic, partially distorted
		0.2565	0.3135	0.22			Yellow	Translucent	85%	Cubic, partially distorted, partially frosted
		0.3135	0.2565	0.21			White	Translucent	85%	Cubic, partially distorted, partially frosted
		0.2850	0.2565	0.17			White	Transparent	85%	Octahedral, twinned
		0.3420	0.2565	0.25			Off White	Transparent	85%	Cubic, partially distorted, graphite inclusions
		0.5415	0.3990	0.25			White	Transparent	Note 1	Fragment on which crystal faces unrecognizable, minor cleavages, graphite inclusions
		0.3135	0.3135	0.29			Yellow	Translucent	85%	Cubic, graphite inclusions
				Subtotal	0.331	0.001655				
	-212/+150 µm	0.2850	0.2280	0.19			White	Translucent	95%	Cubic, graphite inclusions
		0.2280	0.1710	0.18			White	Translucent	85%	Cubic, partially distorted
		0.2280	0.1710	0.17			White	Translucent	85%	Cubic, partially distorted
		0.2565	0.1995	0.22			White	Translucent	85%	Cubic, partially distorted
		0.2565	0.1995	0.18			White	Translucent	85%	Cubic, partially distorted
		0.2565	0.1995	0.2			White	Translucent	85%	Cubic, partially distorted
		0.2280	0.2280	0.19			White	Translucent	85%	Cubic, twinned, partially distorted
		0.2850	0.1995	0.21			White	Transparent	85%	Octahedral, twinned
		0.2565	0.1995	0.26			White	Transparent	85%	Octahedral, twinned
		0.2565	0.1995	0.21			White	Transparent	85%	Octahedral, twinned
		0.1995	0.1710	0.16			White	Transparent	85%	Octahedral, twinned
		0.1995	0.1710	0.14			Off White	Transparent	85%	Octahedral, twinned
		0.2280	0.1995	0.21			White	Transparent	85%	Octahedral, twinned
		0.1710	0.1710	0.11			White	Transparent	95%	Macle, twinned
		0.1995	0.1710	0.12			White	Transparent	95%	Macle, twinned
		0.2280	0.2280	0.18			Off White	Transparent	85%	Octahedral surface fragment
		0.1995	0.1710	0.17			White	Transparent	85%	Octahedral, graphite inclusions
		0.1995	0.1710	0.15			White	Transparent	75%	Fragment with Crystal Faces, very minor cleavages
		0.1995	0.1425	0.18			White	Transparent	85%	Octahedral, twinned
		0.2565	0.1425	0.17			White	Translucent	85%	Octahedral, twinned
		0.2850	0.1995	0.14			Off White	Transparent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages
		0.1995	0.1710	0.14			White	Transparent	62.5%	Fragment with Crystal Faces, very minor cleavages
		0.1995	0.1710	0.11			White	Transparent	85%	Macle surface fragment
				Subtotal	0.277	0.001385				

Appendix 8.1. continued

Sample	Fraction	Stone Dimension (mm)			Weight		Colour	Clarity	Percent Preserv.	Stone Description
		X	Y	Z	(mg)	(Carats)				Morphology
C. cont'd	-150/+105 µm	0.1995	0.1710	0.13			White	Translucent	85%	Cubic
		0.1995	0.1425	0.16			Brown	Transparent	85%	Cubic, partially distorted
		0.1995	0.1710	0.16			White	Translucent	85%	Cubic
		0.1995	0.1995	0.16			White	Translucent	85%	Cubic
		0.1710	0.1710	0.14			Off White	Transparent	85%	Cubic
		0.1710	0.1140	0.12			White	Translucent	85%	Octahedral, twinned
		0.1710	0.1425	0.16			White	Translucent	85%	Cubic, partially distorted
		0.1710	0.1425	0.13			White	Transparent	85%	Octahedral
		0.1425	0.1140	0.13			White	Translucent	85%	Octahedral
		0.1995	0.1425	0.13			White	Transparent	85%	Octahedral, twinned
		0.1425	0.1425	0.11			White	Translucent	85%	Fragment with Crystal Faces
		0.1710	0.1425	0.14			White	Transparent	85%	Cubic, partially distorted
		0.1995	0.1710	0.14			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages, graphite inclusions
		0.2565	0.1425	0.12			White	Transparent	75%	Irregular
		0.1425	0.1140	0.14			White	Transparent	85%	Octahedral
		0.1710	0.1140	0.14			White	Transparent	85%	Octahedral
		0.1425	0.1425	0.16			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages, graphite inclusions
		0.2565	0.1995	0.13			White	Translucent	75%	Fragment with Crystal Faces, very minor cleavages, graphite inclusions
		0.1425	0.1140	0.12			White	Transparent	85%	Octahedral
		0.1995	0.1425	0.11			White	Transparent	85%	Octahedral, twinned
		0.1710	0.1140	0.14			White	Transparent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages
		0.1995	0.1710	0.14			White	Translucent	85%	Fragment with Crystal Faces, very minor cleavages
		0.1710	0.1710	0.15			White	Translucent	85%	Octahedral, twinned
		0.1710	0.1140	0.15			White	Transparent	85%	Octahedral, twinned
		0.1425	0.1425	0.17			White	Translucent	Note 1	Fragment on which crystal faces unrecognizable, minor cleavages
		0.1425	0.1140	0.14			White	Transparent	85%	Octahedral, twinned
		0.1995	0.1425	0.13			White	Transparent	85%	Octahedral, twinned
		0.1140	0.1140	0.14			White	Transparent	85%	Octahedral, twinned
		0.1995	0.1710	0.09			Off White	Transparent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages
		0.1425	0.1140	0.14			White	Transparent	85%	Octahedral, twinned
		0.1995	0.1425	0.14			White	Translucent	85%	Octahedral, twinned
		0.1710	0.1140	0.11			White	Translucent	85%	Cubic surface fragment
		0.1710	0.1710	0.08			White	Transparent	Note 1	Fragment on which crystal faces unrecognizable, very minor cleavages
		0.1710	0.1710	0.11			White	Transparent	85%	Octahedral, twinned
		0.2280	0.1425	0.12			White	Transparent	85%	Octahedral, twinned
		0.1710	0.1140	0.13			White	Translucent	1-55%	Tetrahexahedral
				Subtotal	0.189	0.000945				

Note 1: Diamond Fragments - No Crystal Faces - Preservation (Resorption) cannot be estimated.

*Data as reported by SGS Lakefield Research Limited

9. Project Unit 99-001. Precambrian Geology of the Dinorwic–Butler Lakes Area, Wabigoon Subprovince

G.P. Beakhouse[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

This contribution summarizes observations and preliminary interpretations based on work carried out during the previous summer. This work forms part of a multi-year investigation of the geology of the Wabigoon–Dinorwic lakes area (Beakhouse 2000, 2001, 2002), which was last mapped by Satterly (1943). The area investigated during the 2005 field season overlaps with and extends to the west of the Dinorwic Lake area and this contribution updates a previous report (Beakhouse 2002).

REGIONAL SETTING

The Wabigoon–Dinorwic lakes area is transected by the Wabigoon fault, which is a major regional structure that separates to two geologically distinct domains within the Wabigoon Subprovince. Distinct mineral deposit types and styles also characterize these domains.

The Sioux Lookout domain, lying to the north of the Wabigoon fault, is characterized by a series of alternating sedimentary-dominated and volcanic-dominated panels that consistently face to the south. Many of these panels are regionally interpreted to have fault contacts, however, some of the contacts appear to be conformable depositional contacts with minimal superimposed strain. This area has a complex deformational history with an early, generally bedding parallel fabric (D_1) deformed into a series of megascopic to regional scale, southwest-plunging, Z-asymmetric folds with the development of a second fabric (D_2) parallel to the axial surface of these folds. Metamorphic grade varies regionally from upper greenschist to upper amphibolite with the lowest grade generally occurring nearest to the Wabigoon fault. Gold deposit types in this area include disseminated and vein-type mineralization. Rare-element pegmatites associated with the Ghost Lake batholith occur primarily within the Brownridge volcanics although relatively evolved pegmatites have also been found within the Brownridge sediments to the east of Ghost Lake. Base metal sulphide mineralization is not common although several sulphide mineral occurrences, and possibly related synvolcanic alteration, occur near the stratigraphic top of the Brownridge volcanics.

The Atikwa domain occurs to the south of the Wabigoon fault and is characterized by dominantly volcanic sequences that face away from large, coeval batholiths (e.g., Atikwa Batholith, Aulneau batholith). Within the map area, the Wabigoon metavolcanics are typical of these sequences with a thick basal portion consisting almost entirely of mafic metavolcanic rocks overlain by a more heterolithic portion which, though still dominantly mafic metavolcanic, includes minor intermediate to felsic metavolcanic rocks and rare metasedimentary rocks. South of Wabigoon Lake, the structure is relatively simple with a northward-facing homoclinal sequence characterized by generally weak fabric development except in close proximity to the Wabigoon fault. Mineral assemblages indicative of regional mid- to upper greenschist facies

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.9-1 to 9-6.

© Queen's Printer for Ontario, 2005

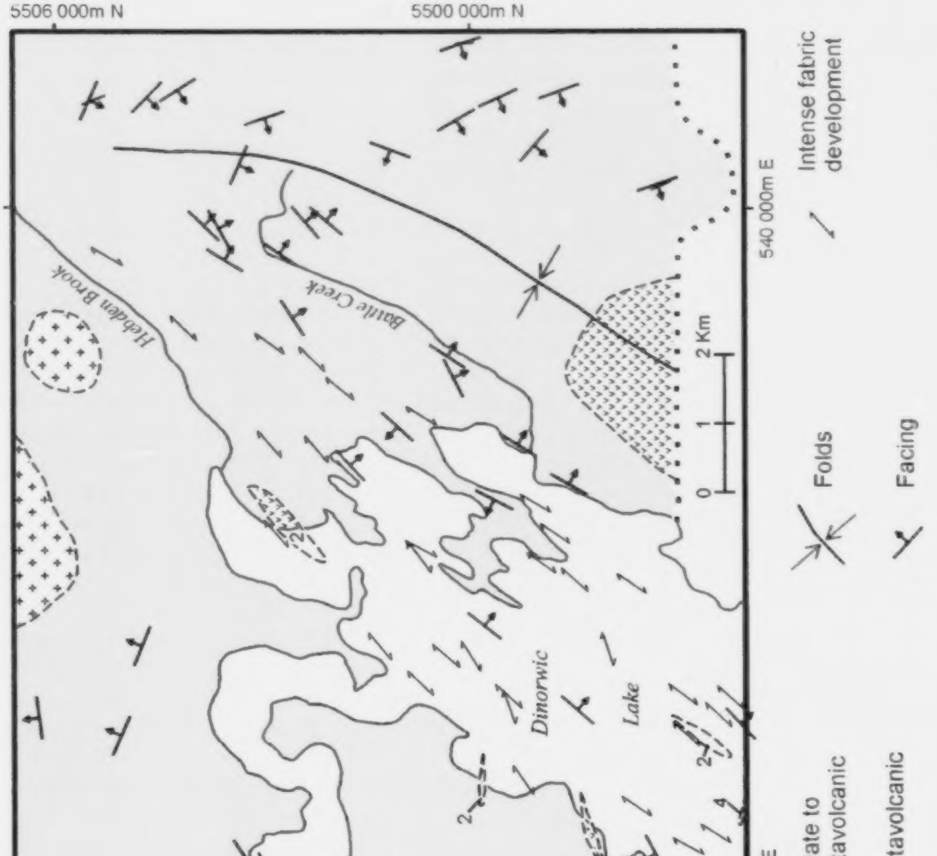

5506 000m N
5500 000m N
540 000m E
530 000m E
Hebden Brook
Battle Creek
Dinorwic
Lake
Wabigoon
Lake
Butler
Lake
0
1
2 Km
2
3
4
Intense fabric development
Folds
Facing
4 Proterozoic diabase dike
3 Intermediate to felsic intrusive rocks
2 Intermediate to felsic metavolcanic rocks
1 Mafic metavolcanic rocks

Figure 9.1. Generalized geology of the Dinorwic–Butler lakes area.

predominate with narrow amphibolitic contact metamorphic aureoles adjacent to some of the plutons. The main mineral exploration targets within the Wabigoon metavolcanics are volcanic-hosted base metal deposits that occur primarily in the upper portion of the sequence and gold mineralization associated with carbonate ± quartz alteration and veining.

LITHOLOGY

The Dinorwic Lake area occurs within the Atikwa domain and, with the exception of several small, late intrusions, is underlain by the Wabigoon metavolcanics (Figure 9.1).

Mafic metavolcanic rocks dominate the Wabigoon metavolcanics in the Dinorwic Lake area. Massive and pillowed flows are approximately equally abundant with minor, widely distributed flow breccia and hyaloclastite. Massive flows range from fine to medium grained. Many of the pillowed flows and some of the massive flows are moderately vesicular. Equigranular flows are most abundant with conspicuous plagioclase porphyritic flows occurring locally. Massive flows include both magnetite-poor (magnetic susceptibility ~0.5–1.0) and magnetite-rich (magnetic susceptibility commonly >50) varieties, whereas the pillowed flows generally have magnetic susceptibilities comparable to the magnetite-poor massive flows. The colour of both weathered and fresh surfaces is highly varied due to a range in intensity of a variety of types of alteration including carbonatization (both calcitic and ferroan carbonate), silicification and epidotization.

Intermediate to felsic metavolcanic rocks are a minor component of the Wabigoon volcanics. Very locally, they form mappable units up to several hundred metres in thickness, but are most commonly thin (<10 m) units interlayered with the predominant mafic metavolcanic rock. Many of these units are relatively massive and their origin is difficult to ascertain. Some units are characterized by the presence of bedding and/or lapilli-size fragments indicating that they are pyroclastic or reworked fragmental deposits. In the Butler Lake area, aphanitic, flow-banded and locally autobrecciated felsic metavolcanic rocks are interpreted to be flows. At least one of these units has geochemical characteristics (Zr = 374 ppm, Y = 37 ppm, Yb =3.8 ppm, Ce_N/Yb_N ~5) transitional between those of F_2 and F_3 rhyolites, both which may be associated with volcanogenic massive sulphide mineralization (Hart, Gibson and Lesher 2004).

Sedimentary rocks are a very minor, widely distributed component of the Wabigoon metavolcanics. Most units contain an end-member, chemical metasedimentary component (chert) with a minor to significant clastic component. Local sulphide-rich zones associated with these horizons are interpreted to be, at least in part, syngenetic. These units are thin (<5 m; mostly <1 m) and have limited lateral extent.

A major west-northwest-trending Proterozoic mafic dike transects the southwestern portion of the map area. This dike system includes a major dike up to 50 m wide that occurs as *en échelon*, left-stepping segments. A number of narrow (generally <1 m), similarly oriented, dikes occur within 100 m of the thick dike and especially in the vicinity of the *en échelon* offsets.

STRUCTURE

The Dinorwic Lake area is divisible into 3 structural domains that are referred to informally as the Butler Lake structural domain (BLSD), Dinorwic Lake structural domain (DLSD) and Jackfish Lake structural domain (JLSD) (Beakhouse 2002). Work carried out during 2005 was primarily within the BLSD and DLSD. Within the BLSD (located to the west of Dinorwic Lake), the Wabigoon volcanics occur in a northward-facing homoclinal sequence. Many of these rocks are characterized by relatively low degrees of strain and have a weakly developed penetrative fabric approximately parallel to bedding. Much of the strain is partitioned into flow contacts, primary fragmental (flow breccia and hyaloclastite units) and interflow sedimentary units; these units are also generally characterized by the most intense, bedding-parallel fabric development.

Locally, a second fabric that may be related to the Dinorwic Lake structural domain (discussed below) transects the bedding and bedding-parallel fabric. This fabric is generally near vertical and trends in a east-northeast direction across much of the BLSD, but deflects into a more northeasterly orientation in proximity to the DLSD.

Within the JLSD, which is situated to the east of Dinorwic Lake, the Wabigoon volcanics are deformed about a disharmonic, closed, north-northeast-trending regional fold that plunges steeply to the southwest (Beakhouse 2002). No additional work was carried out in the JLSD during 2005.

The transition between these structurally distinct portions of the Atikwa domain corresponds to a well-foliated, intensely altered zone that is informally referred to as the Dinorwic Lake structural domain (DLSD) and is characterized by northeast- to north-northeast-trending fabrics. This domain approximately corresponds to the basin of Dinorwic Lake and extends to the north in an area approximately bounded by the northeast-trending segments of Hebden Brook and Battle Creek. The DLSD may be a northward extension of the Manitou Straits fault (Blackburn 1981; Blackburn et al. 1991). The area also corresponds generally to a zone characterized by a lower and less noisy aeromagnetic signature (Beakhouse 2002). The intensity of fabric development within the DLSD ranges from weak to intense, but in general is much more intensely developed than within the bounding domains. A noteworthy feature of this domain is that many of the rocks are extremely fissile, however, the overall state of strain is highly variable based on the geometry of pillows and vesicles. In some cases, highly fissile and altered pillowed mafic volcanics are not highly strained, preserving approximately equant pillow forms in three dimensions. Based on earlier observations, it was proposed that the DLSD may be a zone of dominantly pure shear (Beakhouse 2002). The following observations made during the 2005 field season are relevant to this interpretation and require its revision.

> Asymmetric shear indicators are not common as previously reported (Beakhouse 2002), however, they do occur locally, particularly along the northwestern side of the DLSD. Minor folds occur near the west shore of Dinorwic Lake in the southern portion of the map area and have a consistent S-asymmetry.
>
> Moderately high strain (pillow elongation up to 10:1 in horizontal exposures) occurs locally with the flattening fabric oriented approximately 20-30° clockwise from, and locally deflecting into, the throughgoing, north-northeast-trending zones of highly fissile rock.
>
> Magnetic patterns suggest that the southeast-trending stratigraphy in the BLSD deflects into a more easterly or even northeasterly orientation in proximity to the DLSD.

These observations suggest that this broad, fissile, intensely altered zone, although dominantly characterized by pure shear, does contain discrete shear zones with a sinistral sense of displacement. These shear zones are largely concealed beneath extensive water covered or poorly exposed areas. The northeast-trending fabric within the BLSD appears to be related to the flattening fabric associated with this sinistral transcurrent deformation in the DLSD.

ALTERATION

Rocks in the Dinorwic Lake area are locally moderately to intensely altered. This alteration includes both local, stratigraphically controlled alteration as well as more pervasive, regional, structurally controlled alteration that are described separately below.

Local Stratigraphically Controlled Alteration

Throughout much of the Dinorwic Lake area outside of the DLSD, metavolcanic rocks are well preserved and characterized by very weak fabric development and weak background alteration with local zones of more intense alteration and fabric development. The background alteration consists of calcitic carbonate and less abundant epidote that has filled primary porosity (vesicles and interpillow spaces) and also occurs as fine-grained disseminated grains. Locally, interpillow carbonate encloses delicate, platy, exfoliated pillow selvage material. These observations suggest that this background alteration is related to synvolcanic to early diagenetic seawater alteration.

The more intense alteration observed locally is characterized by the presence of reddish weathering carbonate that is interpreted to reflect its more iron-rich (ferroan dolomite or ankerite) composition. This iron-bearing carbonate occurs as disseminations and in veins along with varying proportions of quartz and calcitic carbonate. This type of alteration is associated with specific rocks types and stratigraphic contacts including 1) flow contacts, especially with brecciated flow tops; 2) chert ± sulphide units; and 3) thin interflow intermediate to felsic tuffaceous units. These units also characteristically have more conspicuous fabric development and have accommodated much of the strain. These structural attributes have undoubtedly played a role in generating the porosity and permeability that is responsible for this type of alteration being localized in these zones, but their development is itself strongly influenced by stratigraphy and the associated synvolcanic to early diagenetic development of hydrous mineral assemblages.

The more intense alteration is interpreted to be relatively late based on the weakly deformed to undeformed character of veins. Locally, iron carbonate is observed to fill primary porosity and enclose delicate primary fragments as described above. This observation suggests that the iron-bearing carbonate overprints and locally replaces the early calcitic carbonate alteration.

Regional Structurally Controlled Alteration

Throughout large portions of the Dinorwic Lake area, moderate to intense alteration is developed within and marginal to highly fissile zones that trend northeast to north-northeast. On a regional scale, this style of alteration is centred on the DLSD, much of which is moderately to intensely altered. However, this style of alteration also occurs along narrow, more widely spaced, north-northeast- to northeast-trending structures within the BLSD and JLSD.

The most extensive type of alteration consists of disseminated reddish-brown weathering iron carbonate. Moderately deformed to undeformed veins consisting of iron carbonate and quartz in a range of proportions commonly occur along with the disseminated style of mineralization. Small areas within the regional iron carbonate alteration are characterized by massive and pillowed mafic metavolcanic rocks with a very light gray colour and splintery fracture and are provisionally interpreted as zones of silicification. Quartz veining that is possibly related to this silicification contains angular fragments of iron carbonatized wall rock suggesting that the silicification may postdate the regional iron carbonate alteration.

On regional as well as more local scales, this type of alteration is spatially associated with northeast- to north-northeast-trending zones characterized by being highly fissile though not necessarily highly strained. Characteristically, the alteration extends beyond the highly fissile zone into rocks that possess a very weak mineral foliation. The width of these zones is highly varied, but may be up to several hundred metres wide. Veining may be present throughout the zone of pervasive disseminated iron-bearing carbonate, but, in some cases, is observed to be most abundant in the fissile core and/or the outer edges of these alteration zones. The large area of iron carbonate alteration associated with the DLSD may represent numerous closely spaced zones of this type.

MINERALIZATION

The Dinorwic Lake area has potential for syngenetic, volcanic-hosted, base metal mineralization and late disseminated and vein-hosted gold mineralization. The most favourable area for base metal mineralization may be the central and upper portion of the Wabigoon volcanics stratigraphy. This interpretation is based on the presence of F_2–F_3 rhyolite and dominantly pyritic sulphide occurrences that are either associated with cherty interflow metasedimentary horizons or occur within pillowed mafic metavolcanic rocks.

Known occurrences of gold mineralization in the area are associated with quartz-carbonate veining containing one or more of tourmaline, pyrite, arsenopyrite, chalcopyrite and tetrahedrite (Parker 1989).

Veins of this type are widespread within both the regional, north-northeast-trending alteration zones and the more localized stratigraphically controlled alteration zones described above and there is good potential for the discovery of additional gold mineralization.

Regional-scale iron carbonate alteration in the Southworth Township area is considered to be favourable for gold mineralization. The general pattern of regional-scale iron carbonate alteration with background (distal) calcitic carbonate containing more localized zones of silicification and veining observed in the Dinorwic Lake area is comparable in many respects with that described for the Red Lake gold camp area (Parker 2000). The main differences between the two areas include the presence of abundant ultramafic metavolcanic rock in the Red Lake area and the interpretation that the background calcitic carbonate alteration in the Dinorwic Lake area significantly predates iron carbonate alteration. These differences notwithstanding, the large area of iron carbonate alteration within Southworth Township is proposed as a prime target for gold exploration. Northeast- to east-northeast-trending zones within the BLSD and JLSD may be related to deformation and alteration associated with the DLSD and are also prospective.

REFERENCES

Beakhouse, G.P. 2000. Precambrian geology of the Wabigoon area; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p.20-1 to 20-8.

——— 2001. Precambrian geology of the Thunder Lake segment, Wabigoon area; *in* Summary of Field Work and Other Activities 2001, Ontario Geological Survey, Open File Report 6070, p.15-1 to 15-6.

——— 2002. Precambrian geology of the Dinorwic area, Wabigoon Subprovince; *in* Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.10-1 to 10-6.

Blackburn, C.E. 1981. Kenora–Fort Frances, geological compliation series, Kenora and Thunder Bay districts; Ontario Geological Survey, Map 2443, scale 1:253 440.

Blackburn, C.E., Johns, G.W., Ayer, J. and Davis, D.W. 1991. Wabigoon subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.303-381.

Hart, T.R., Gibson, H.L. and Lesher, C.M. 2004. Trace element geochemistry and petrogenesis of felsic volcanic rocks associated with volcanogenic massive Cu-Zn-Pb sulfide deposits; Economic Geology, v.99, p.1003-1013.

Parker, J.R. 1989. Geology, gold mineralization and property visits in the area investigated by the Dryden–Ignace economic geologist, 1984–1987; Ontario Geological Survey, Open File Report 5723, 306p.

——— 2000. Gold mineralization and wall rock alteration in the Red Lake greenstone belt: A regional perspective; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p. 22-1 to 22-27.

Satterly, J. 1943. Geology of the Dryden–Wabigoon area; Ontario Department of Mines, Annual Report, 1941, Volume 50, Part 2, p.1-67.

10. Project Unit 03-011. Discrimination of Archean Domains in the Sachigo Subprovince: A Progress Report on the Geochronology

N. Rayner[1] and G.M. Stott[2]

[1]Geological Survey of Canada, Ottawa, Ontario
[2]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario

INTRODUCTION

For many years, a very large part of the northern Superior Province in Ontario had been lumped under the term "Sachigo Subprovince" (Card and Ciesielski 1986; *see also* Stott and Rayner 2004, Figure 10.1) from the Hudson Bay Lowlands to the Berens River Subprovince. This provided a useful label for a broad territory characterized by narrow, southeast-trending, curviplanar greenstone belts in contrast to the more eastward trends of belts in the southern half of the Superior Province in Ontario. However, improvements in our knowledge of the geochronology and geochemistry in the Sachigo Subprovince are providing greater discrimination and subdivision of this region. An overview of the current state of knowledge and the objectives of this project is given in Stott and Rayner (2004).

The main intent of this project is to improve our understanding of the broad tectonic subdivisions of Archean crust in the northern part of the Sachigo Subprovince in Ontario (Figure 10.1, which shows our current interpretation based on results presented here combined with previous work by Stone (2005) and others (e.g., Skulski et al. 2000) in the Stull Lake region near the Ontario–Manitoba border). This is being done by searching for a broad pattern of rock ages and whole rock Nd model ages across a north-south transect from the Hudson Bay Lowlands to the eastern extension of the Wunnummin greenstone belt (Figure 10.2). We obtained a suite of reconnaissance samples for U/Pb zircon geochronology and Nd isotopic tracer studies. These include mostly felsic plutonic rocks, a felsic volcanic unit, and samples of quartz arenite unconformably overlying the Archean basement at 2 widely separated sites. Sampling of outcrops and drill core was done with the co-operation of staff from De Beers Canada Exploration Inc., Wallbridge Mining Co. Ltd. and Spider Resources Inc. (Stott and Rayner 2004). This report provides the principal results from Nd isotopic and U/Pb zircon analyses.

METHODS

Zircons were separated from the drill core samples using standard crushing, heavy liquid and magnetic separation techniques. Sensitive high-resolution ion microprobe (SHRIMP) analytical procedures followed those described by Stern (1997), with standards and U/Pb calibration methods following Stern and Amelin (2003). Briefly, zircons were cast in 2.5 cm diameter epoxy mounts (GSC #325, 334 and 355) along with fragments of the GSC laboratory standard zircon (z6266, ^{206}Pb/^{238}U age = 559 Ma). The mid-sections of the zircons were exposed using 9, 6, and 1 µm diamond compound, and the internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized in back-scattered electron mode (BSE) utilizing a Cambridge Instruments scanning electron microscope. Mount

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.10-1 to 10-21

© Queen's Printer for Ontario, 2005

surfaces were evaporatively coated with 10 nm of high purity Au. Analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. Two different spot sizes were used in the analysis of the basement sample zircons. A larger spot (K120 aperture, circa 25 μm in diameter) with a beam current of circa 12 nA was used to target cores and zircons composed of a single generation of growth. A smaller spot (K70 aperture, circa 12 μm in diameter) with a beam current of circa 2 nA was used to target thin rims. The detrital zircons from the sedimentary samples were analysed in a separate analytical session where only the larger spot size was used. The count rates of ten isotopes of Zr+, U+, Th+, and Pb+ were sequentially measured over 6 scans (basement samples) or 5 scans (sedimentary samples). A single electron multiplier and a pulse counting system with deadtime of 35 ns were used. Off-line data processing was accomplished using customized in-house software. The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in the data table incorporate a ±1.0% error in calibrating the standard zircon (*see* Stern and Amelin 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the Pb composition of the surface blank (Stern 1997). Isoplot v.3.00 (Ludwig 2003) was used to generate concordia plots and calculate weighted mean ages. AgeDisplay (Sircombe 2004) was used to generate cumulative probability curves and histograms for the detrital zircon data.

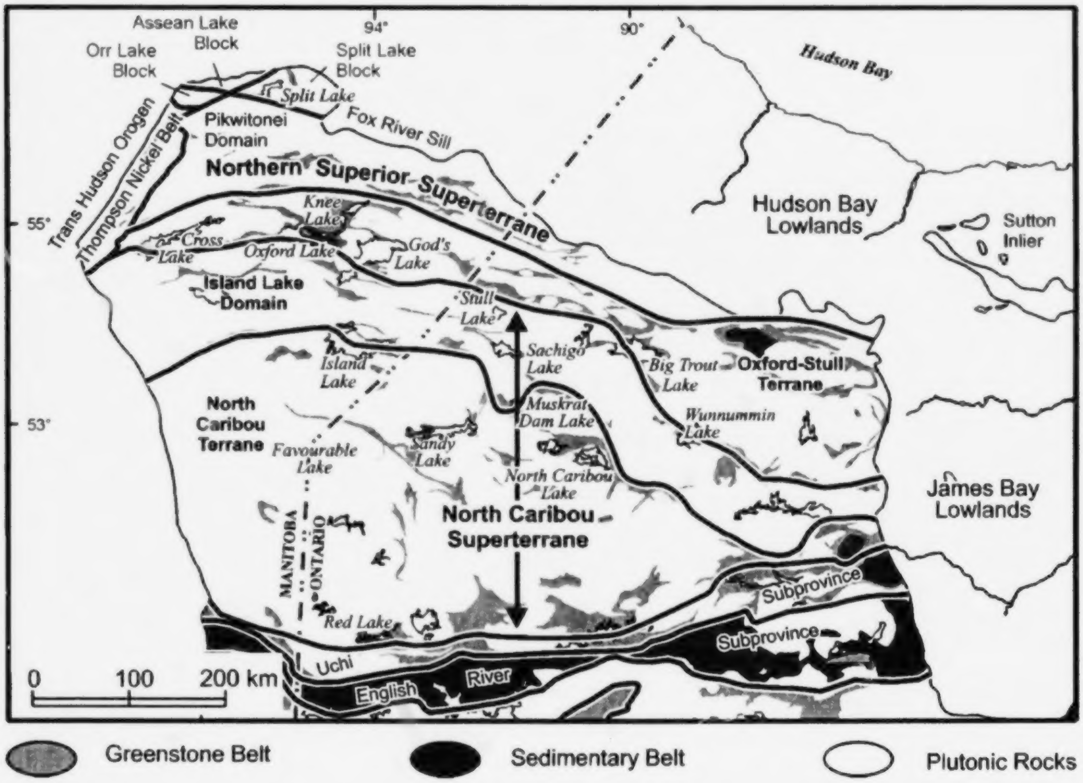

Assean Lake Block
Orr Lake Block
94°
Split Lake Block
90°
Hudson Bay
Split Lake
Pikwitonei Domain
Fox River Sill
Trans Hudson Orogen
Thompson Nickel Belt
Northern Superior Superterrane
55°
Knee Lake
Cross Lake
Oxford Lake
God's Lake
Hudson Bay Lowlands
Sutton Inlier
Island Lake Domain
Stull Lake
Sachigo Lake
Big Trout Lake
Oxford-Stull Terrane
Island Lake
53°
North Caribou Terrane
Muskrat Dam Lake
Wunnummin Lake
Favourable Lake
Sandy Lake
North Caribou Lake
James Bay Lowlands
North Caribou Superterrane
MANITOBA
ONTARIO
Subprovince
Red Lake
Subprovince
0 100 200 km
Uchi
English
River
Greenstone Belt
Sedimentary Belt
Plutonic Rocks

Figure 10.1. A tentative subdivision of the northern Superior Province into terranes in Ontario and Manitoba (*modified from* Stone 2005) to illustrate the current difficulties of subdivisions within Ontario. A major collisional boundary is apparent between the North Caribou superterrane and most of the linear Wunnummin Lake greenstone belt, which might form the southern margin of the Oxford–Stull terrane. The extension of the Island Lake terrane eastward remains speculative. Likewise, considerable uncertainty remains about the eastward extension of the boundary between the Northern Superior superterrane and the Oxford–Stull terrane.

Tracer isotopic analyses were conducted using the multicollector inductively coupled plasma mass spectrometer (ICP–MS) Nu Plasma. Since Sm and Nd were eluted from the Ln-Spec columns in dilute HNO_3, the Nd and Sm solutions were measured directly without additional chemical conversions. Samarium and Nd were analyzed using an array of fixed Faraday collectors in static multicollector mode. The isotopic ratios were corrected for spike contribution and mass discrimination by numeric solution of the isotope dilution equations with exponential normalization. Quality control was performed by monitoring the uniformity of non-radiogenic isotopic ratios: $^{145}Nd/^{144}Nd$, $^{150}Nd/^{144}Nd$, $^{150}Sm/^{152}Sm$ and $^{154}Sm/^{152}Sm$. The quality of the data was also monitored by analyzing of the standards (La Jolla Nd and Ames Sm). The $^{143}Nd/^{144}Nd$ ratios in the samples are reported relative to $^{143}Nd/^{144}Nd$=0.51186 in the La

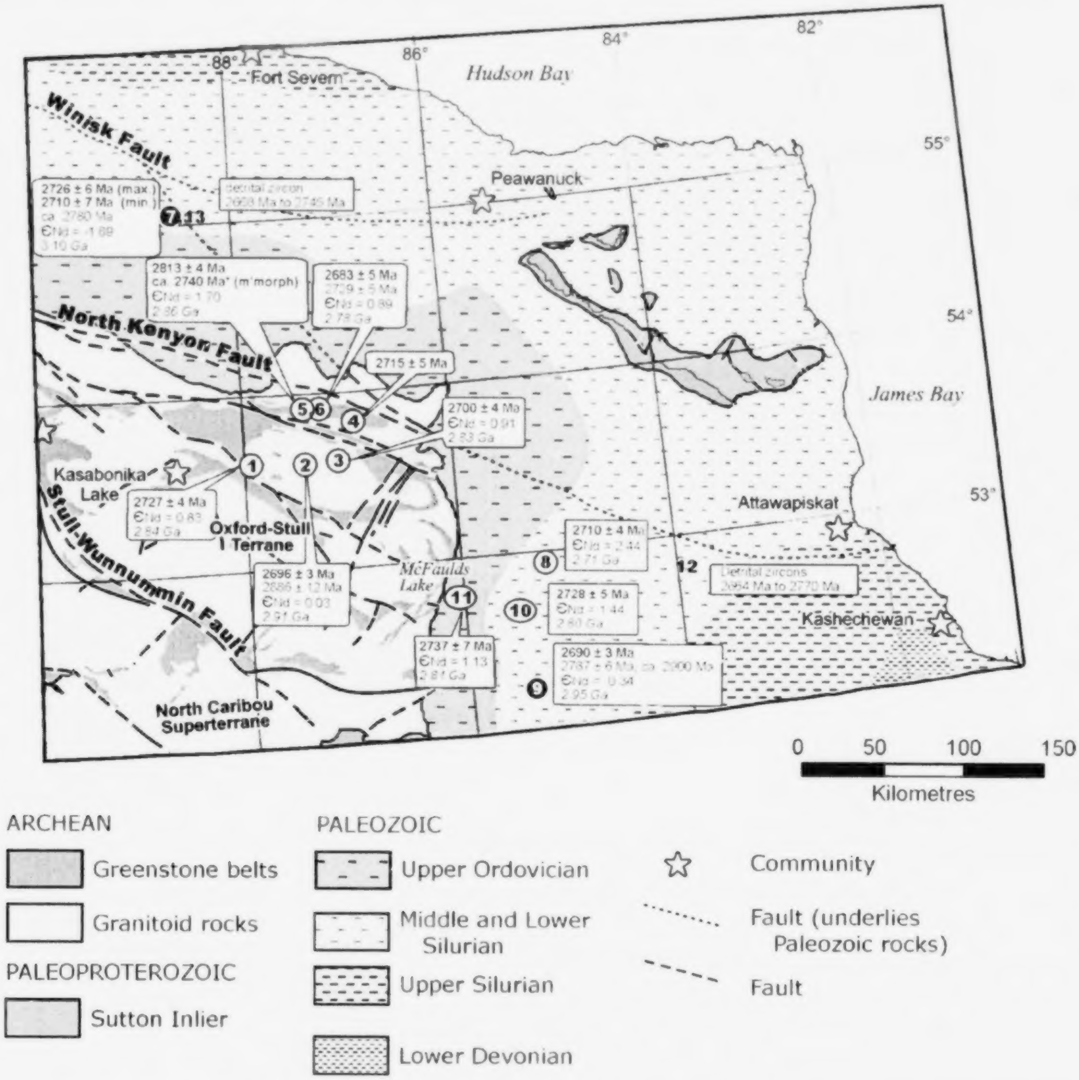
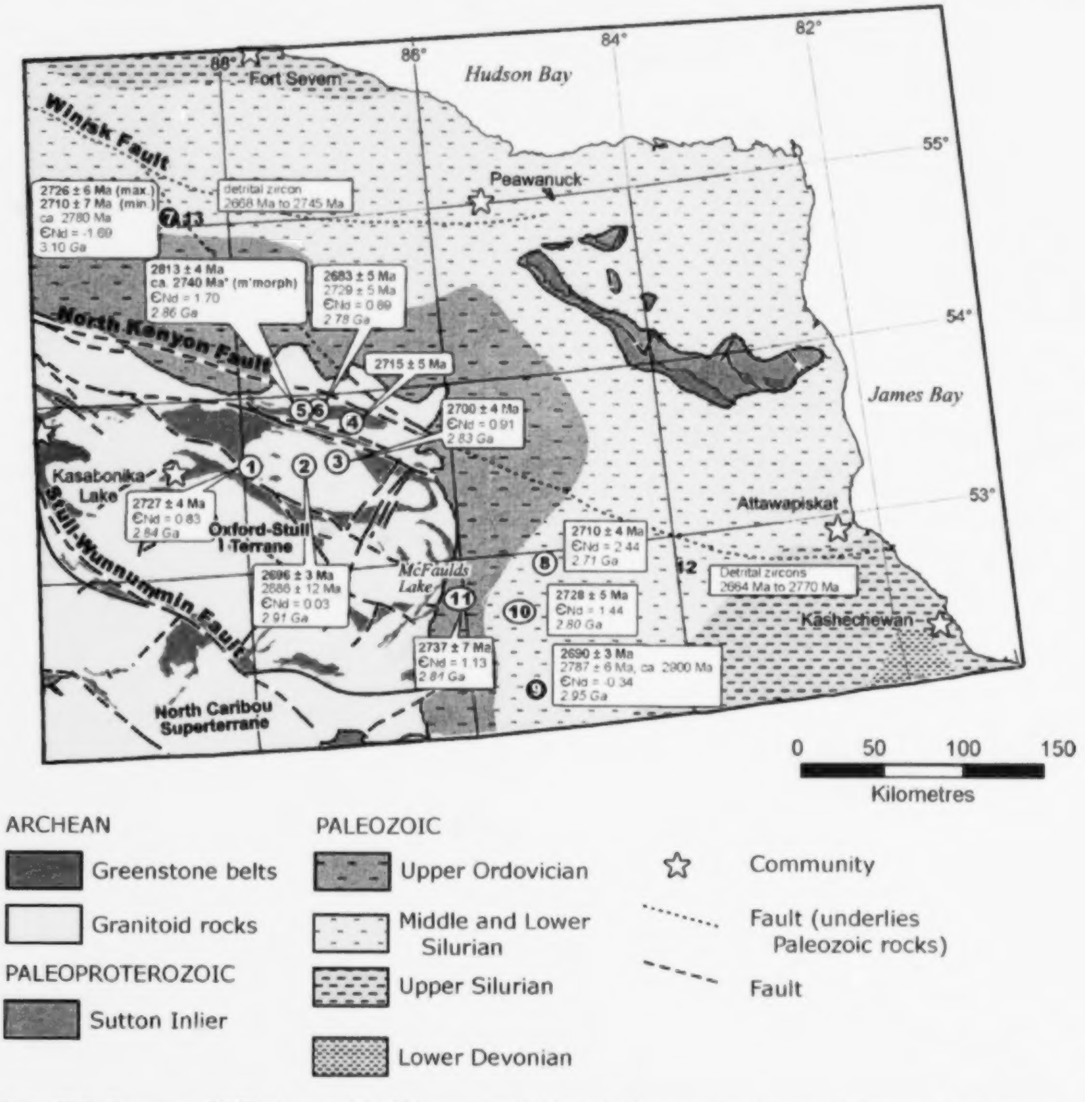

88°
86°
84°
82°
Fort Severn
Hudson Bay
55°
54°
53°
Winisk Fault
Peawanuck
2726 ± 6 Ma (max.)
2710 ± 7 Ma (min.)
ca. 2780 Ma
ЄNd = -1.69
3.10 Ga
detrital zircon
2698 Ma to 2745 Ma
7
13
2813 ± 4 Ma
ca. 2740 Ma* (m'morph)
ЄNd = 1.70
2.86 Ga
2683 ± 5 Ma
2729 ± 5 Ma
ЄNd = 0.89
2.78 Ga
North Kenyon Fault
2715 ± 5 Ma
5
6
4
2700 ± 4 Ma
ЄNd = 0.91
2.83 Ga
James Bay
1
2
3
Kasabonika Lake
2727 ± 4 Ma
ЄNd = 0.83
2.84 Ga
Oxford-Stull Terrane
Attawapiskat
Stull-Wunnummin Fault
2710 ± 4 Ma
ЄNd = 2.44
2.71 Ga
8
12
Detrital zircons
2684 Ma to 2770 Ma
2696 ± 3 Ma
2886 ± 12 Ma
ЄNd = 0.03
2.91 Ga
McFaulds Lake
11
10
2728 ± 5 Ma
ЄNd = 1.44
2.80 Ga
Kashechewan
2737 ± 7 Ma
ЄNd = 1.13
2.81 Ga
2690 ± 3 Ma
2787 ± 6 Ma, ca. 2900 Ma
ЄNd = -0.34
2.95 Ga
9
North Caribou Superterrane
0
50
100
150
Kilometres
ARCHEAN
Greenstone belts
Granitoid rocks
PALEOPROTEROZOIC
Sutton Inlier
PALEOZOIC
Upper Ordovician
Middle and Lower Silurian
Upper Silurian
Lower Devonian
Community
Fault (underlies Paleozoic rocks)
Fault

Figure 10.2. Summary of U/Pb zircon and Sm/Nd tracer results from sub-Phanerozoic and exposed basement in northwestern Ontario. Locations 1 to 13 correspond to the samples described in the text. Uranium-lead (U/Pb) zircon crystallization ages determined by SHRIMP are shown in bold type. Ages of inherited zircon are shown in normal type. Neodymium model ages (DePaolo 1981, depleted-mantle model) are shown in italic type. Black circled sites possess $\varepsilon_{Nd} < 0$ and for white circled sites, ε_{Nd} is > 0. *See text for discussion regarding location 5.

Tracer isotopic analyses were conducted using the multicollector inductively coupled plasma mass spectrometer (ICP–MS) Nu Plasma. Since Sm and Nd were eluted from the Ln-Spec columns in dilute HNO_3, the Nd and Sm solutions were measured directly without additional chemical conversions. Samarium and Nd were analyzed using an array of fixed Faraday collectors in static multicollector mode. The isotopic ratios were corrected for spike contribution and mass discrimination by numeric solution of the isotope dilution equations with exponential normalization. Quality control was performed by monitoring the uniformity of non-radiogenic isotopic ratios: ^{145}Nd/^{144}Nd, ^{150}Nd/^{144}Nd, ^{150}Sm/^{152}Sm and ^{154}Sm/^{152}Sm. The quality of the data was also monitored by analyzing of the standards (La Jolla Nd and Ames Sm). The ^{143}Nd/^{144}Nd ratios in the samples are reported relative to ^{143}Nd/^{144}Nd=0.51186 in the La



88°
86°
84°
82°
55°
54°
53°
Fort Severn
Hudson Bay
James Bay
Peawanuck
Attawapiskat
Kashechewan
Kasabonika Lake
McFaulds Lake
Winisk Fault
North Kenyon Fault
Stull-Wunnummin Fault
Oxford-Stull Terrane
North Caribou Superterrane
2726 ± 6 Ma (max.) 2710 ± 7 Ma (min.) ca. 2780 Ma εNd = -1.69 3.10 Ga
7 13
detrital zircon 2668 Ma to 2745 Ma
2813 ± 4 Ma ca. 2740 Ma* (m'morph) εNd = 1.70 2.86 Ga
2683 ± 5 Ma 2729 ± 5 Ma εNd = 0.89 2.78 Ga
2715 ± 5 Ma
2700 ± 4 Ma εNd = 0.91 2.83 Ga
5 6 4 1 2 3
2727 ± 4 Ma εNd = 0.83 2.84 Ga
2696 ± 3 Ma 2886 ± 12 Ma εNd = 0.03 2.91 Ga
2710 ± 4 Ma εNd = 2.44 2.71 Ga
8
12
Detrital zircons 2664 Ma to 2770 Ma
2728 ± 5 Ma εNd = 1.44 2.80 Ga
10
11
2737 ± 7 Ma εNd = 1.13 2.81 Ga
2690 ± 3 Ma 2787 ± 6 Ma, ca. 2800 Ma εNd = -0.34 2.95 Ga
9
0 50 100 150
Kilometres
ARCHEAN
Greenstone belts
Granitoid rocks
PALEOPROTEROZOIC
Sutton Inlier
PALEOZOIC
Upper Ordovician
Middle and Lower Silurian
Upper Silurian
Lower Devonian
Community
Fault (underlies Paleozoic rocks)
Fault

Figure 10.2. Summary of U/Pb zircon and Sm/Nd tracer results from sub-Phanerozoic and exposed basement in northwestern Ontario. Locations 1 to 13 correspond to the samples described in the text. Uranium-lead (U/Pb) zircon crystallization ages determined by SHRIMP are shown in bold type. Ages of inherited zircon are shown in normal type. Neodymium model ages (DePaolo 1981, depleted-mantle model) are shown in italic type. Black circled sites possess $\varepsilon_{Nd} < 0$ and for white circled sites, ε_{Nd} is > 0. *See text for discussion regarding location 5.

Jolla standard. The correction is applied using average measured $^{143}Nd/^{144}Nd$ in the La Jolla standard of 0.511811±0.000012 (2σ), measured during the course of this study. The ε ^{143}Nd is calculated using the igneous age determined by SHRIMP (this study). Neodymium model ages (TDM) were calculated according to the model of DePaolo (1981).

RESULTS

The U/Pb zircon results are summarized below, presented in data Table 10.1, and in the concordia diagrams and histograms (Figures 10.3, 10.4 and 10.5). Examples of zircon images are shown in Figures 10.6 and 10.7. For clarity, the samples are subdivided into three groups: exposed basement samples (*see* Figure 10.2, location numbers 1 to 6), basement samples from beneath the Phanerozoic sediments sampled by drill core (*see* Figure 10.2, locations 7 to 11) and basal sedimentary samples (*see* Figure 10.2, locations 12 and 13). The errors on the individual spots reported in Table 10.1 are given at the 1σ uncertainty level. The ellipses on the concordia diagrams are plotted at 2σ, as are the errors of the mean ages given below. Location numbers on Figure 10.2 are given below for each of the samples described.

Basement Samples: Outcrop

Location 1. Sample 03GRS-013 is a tonalite-quartz diorite. The dominant population of zircons contains low U concentrations and broad oscillatory zones. Sixteen analyses give a weighted mean $^{207}Pb/^{206}Pb$ age of 2727±4 Ma (grey ellipses on the concordia diagram of Figure 10.3a, mean square of weighted deviates (MSWD) = 0.60, probability of fit = 88%). This is interpreted as the time of crystallization. Three analyses of small, moderate U domains yield younger results (unshaded ellipses, 2702, 2704 and 2709 Ma), which may indicate a younger episode of zircon growth. However, these three analyses are statistically indistinguishable from the 2727 Ma zircon and, therefore, we cannot confidently establish the existence of distinctly younger zircon. There is no evidence from the results, or any indication in the images of the zircons, of any older inherited cores.

Location 2. Sample 03GRS-014 is a granodiorite. Zircons are composed of high U, fine-oscillatory zoned rims around low U, zoned cores. Thirteen analyses of the high U zircon (11 different zircon grains) give a weighted mean $^{207}Pb/^{206}Pb$ age of 2696±3 Ma (light grey ellipses on Figure 10.3b, MSWD = 1.3, probability of fit = 22%). This is interpreted as the time of crystallization. Analysis of six cores gives a weighted mean $^{207}Pb/^{206}Pb$ age of 2886±12 Ma (dark grey ellipses, MSWD = 0.89, probability of fit = 49%). These zircons are interpreted as inherited or xenocrystic.

Location 3. Sample 03GRS-015 is a biotite tonalite gneiss. Zircons from this sample have a wide range of U content (75 ppm to 2200 ppm), contain well-developed oscillatory zoning, but are locally highly altered and fractured. Unaltered areas within the altered zircon grains were targeted for analysis. Eleven analyses give a weighted mean $^{207}Pb/^{206}Pb$ age of 2700±4 Ma (light grey ellipses on Figure 10.3c, MSWD = 1.6, probability of fit = 9%). This is interpreted as the time of crystallization. Four analyses were excluded from the calculation of the weighted mean: one highly discordant grain (#29, see data table for details), one analysis with extreme U content (#12) as well as 3 older zircons that are interpreted as inherited or xenocrystic (grain #2, #27 and #5; 2723 Ma, 2726 Ma and 2742 Ma, respectively).

Location 4. Sample 03GRS-016 is a biotite tonalite to granodiorite. The zircons contain well-developed oscillatory zoning, but are moderately altered and fractured. Fourteen analyses give a weighted mean $^{207}Pb/^{206}Pb$ age of 2715±5 Ma (grey ellipses on Figure 10.3d, MSWD = 1.0, probability of fit = 41%). This is interpreted as the time of crystallization. One high U analysis was excluded (white ellipse) from the calculation of the weighted mean due to likely Pb-loss from the zircon after crystallization.

Table 10.1. Summary of U/Pb isotopic data for zircon from a selected suite of plutonic, volcanic and sedimentary rocks from sites located on Figure 10.2.

Spot name	U (ppm)	Th (ppm)	$\frac{Th}{U}$	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	$f(206)^{204}$	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Age (Ma) $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)	spot size
Location #1 (03GRS-013)																							
Tonalite-quartz diorite																							
8105-3.1	162	134	0.85	103	3	4.86E-05	1.25E-05	0.00084	0.23834	0.00281	13.448	0.157	0.5171	0.0056	0.9606	0.1886	0.0006	2687	24	2730	5	1.6	25μm
8105-8.1	186	132	0.73	115	1	1.72E-05	1.22E-05	0.00030	0.20419	0.00298	13.361	0.164	0.5143	0.0057	0.9434	0.1884	0.0008	2675	24	2728	7	2	25μm
8105-13.1	226	201	0.92	142	3	2.57E-05	1.22E-05	0.00045	0.25472	0.00259	13.182	0.170	0.5074	0.0056	0.9071	0.1884	0.0010	2645	24	2729	9	3	25μm
8105-16.1	102	85	0.86	64	3	6.62E-05	1.91E-05	0.00115	0.24102	0.00441	13.351	0.209	0.5134	0.0073	0.9490	0.1886	0.0009	2671	31	2730	8	2.2	25μm
8105-22.1	202	142	0.73	122	0	2.76E-06	9.57E-06	0.00005	0.20623	0.00227	13.073	0.150	0.5042	0.0054	0.9630	0.1880	0.0006	2632	23	2725	5	3.4	25μm
8105-24.1	134	117	0.91	84	4	6.75E-05	1.83E-05	0.00117	0.24889	0.00652	13.114	0.177	0.5056	0.0060	0.9258	0.1881	0.0010	2638	26	2726	9	3.2	25μm
8105-33.1	163	124	0.78	100	4	6.27E-05	2.40E-05	0.00109	0.21669	0.00372	13.145	0.157	0.5079	0.0055	0.9491	0.1877	0.0007	2648	24	2722	6	2.7	25μm
8105-67.1	147	111	0.78	91	4	5.55E-05	1.44E-05	0.00096	0.21495	0.00270	13.284	0.154	0.5126	0.0055	0.9617	0.1879	0.0006	2668	24	2724	5	2.1	25μm
8105-54.1	90	96	1.10	59	3	8.75E-05	3.02E-05	0.00152	0.30494	0.00660	13.400	0.187	0.5130	0.0064	0.9311	0.1895	0.0010	2669	27	2738	8	2.5	25μm
8105-26.1	123	121	1.01	80	3	4.74E-05	1.77E-05	0.00082	0.28024	0.00352	13.233	0.169	0.5112	0.0059	0.9464	0.1877	0.0008	2662	25	2722	7	2.2	25μm
8105-4.1	174	116	0.69	106	4	5.43E-05	1.10E-05	0.00094	0.18982	0.00469	13.282	0.167	0.5125	0.0059	0.9501	0.1880	0.0008	2667	25	2725	7	2.1	25μm
8105-11.1	167	122	0.75	102	5	6.34E-05	2.01E-05	0.00110	0.20823	0.00254	13.202	0.158	0.5108	0.0056	0.9546	0.1874	0.0007	2660	24	2720	6	2.2	25μm
8105-7.1	216	199	0.95	143	26	2.63E-04	8.07E-05	0.00455	0.27081	0.00678	13.513	0.235	0.5285	0.0063	0.7622	0.1854	0.0021	2735	26	2702	19	-1.2	**
8105-14.1	272	223	0.85	172	19	1.56E-04	3.40E-05	0.00270	0.22729	0.00508	13.296	0.244	0.5196	0.0070	0.8095	0.1856	0.0020	2697	30	2704	18	0.2	**
8105-58.1	220	154	0.73	137	21	2.13E-04	4.24E-05	0.00370	0.19345	0.01113	13.506	0.212	0.5260	0.0068	0.8779	0.1862	0.0014	2725	29	2709	13	-0.6	**
8105-69.1	233	167	0.74	147	31	2.99E-04	8.19E-05	0.00517	0.21180	0.00563	13.711	0.256	0.5233	0.0078	0.8611	0.1900	0.0018	2713	33	2742	16	1.1	**
8105-58.2	119	112	0.97	80	17	3.20E-04	6.87E-05	0.00555	0.27164	0.00822	13.842	0.262	0.5306	0.0081	0.8718	0.1892	0.0018	2744	34	2735	15	-0.3	**
8105-59.1	191	141	0.76	122	15	1.69E-04	4.27E-05	0.00293	0.21279	0.00880	13.792	0.220	0.5314	0.0072	0.9031	0.1882	0.0013	2747	30	2727	11	-0.7	**
8105-25.1	176	115	0.67	109	17	2.19E-04	5.54E-05	0.00380	0.18340	0.00685	13.692	0.211	0.5214	0.0067	0.8861	0.1905	0.0014	2705	28	2746	12	1.5	**
Location #2 (03GRS-014)																							
Granodiorite																							
8108-5.1	1121	125	0.115	617	6	1.23E-05	4.69E-06	0.00021	0.03149	0.00035	13.296	0.185	0.5269	0.0065	0.9329	0.1830	0.0009	2728	28	2680	8	-1.8	25μm
8108-23.1	809	153	0.195	452	7	2.04E-05	9.75E-06	0.00035	0.05130	0.00080	13.297	0.187	0.5252	0.0062	0.8979	0.1836	0.0012	2721	26	2686	10	-1.3	25μm
8108-60.1	1129	166	0.152	629	8	1.51E-05	6.30E-06	0.00026	0.04145	0.00046	13.418	0.176	0.5291	0.0060	0.9192	0.1839	0.0010	2738	25	2689	9	-1.8	25μm
8108-15.1	1483	220	0.153	843	5	6.86E-06	5.96E-06	0.00012	0.04203	0.00058	13.688	0.155	0.5385	0.0056	0.9608	0.1844	0.0006	2777	24	2692	5	-3.2	25μm
8108-7.1	287	123	0.444	171	3	2.45E-05	9.97E-06	0.00042	0.12431	0.00219	13.429	0.179	0.5281	0.0059	0.8965	0.1844	0.0011	2734	25	2693	10	-1.5	25μm
8108-2.1	784	212	0.279	441	9	2.64E-05	7.69E-06	0.00046	0.07509	0.00115	13.204	0.150	0.5192	0.0057	0.9848	0.1845	0.0004	2696	24	2693	3	-0.1	25μm
8108-2.2	1852	198	0.110	1037	8	9.94E-06	3.41E-06	0.00017	0.03047	0.00024	13.637	0.168	0.5360	0.0063	0.9828	0.1846	0.0004	2766	27	2694	4	-2.7	25μm
8108-16.1	1562	193	0.128	890	9	1.18E-05	3.62E-06	0.00020	0.03430	0.00038	13.830	0.183	0.5435	0.0070	0.9893	0.1846	0.0004	2798	29	2694	3	-3.8	25μm
8108-49.1	949	94	0.103	521	4	8.19E-06	1.08E-05	0.00014	0.02883	0.00066	13.409	0.185	0.5262	0.0063	0.9221	0.1848	0.0010	2725	27	2697	9	-1.1	25μm
8108-19.1	890	209	0.242	504	4	9.19E-06	5.69E-06	0.00016	0.06723	0.00074	13.397	0.150	0.5256	0.0055	0.9642	0.1849	0.0006	2723	23	2697	5	-1	25μm
8108-40.2	1455	275	0.195	828	5	7.55E-06	6.56E-06	0.00013	0.05369	0.00041	13.622	0.164	0.5340	0.0062	0.9833	0.1850	0.0004	2758	26	2698	4	-2.2	25μm
8108-57.1	1017	184	0.187	567	6	1.31E-05	5.24E-06	0.00023	0.05153	0.00044	13.396	0.180	0.5238	0.0065	0.9627	0.1855	0.0007	2715	28	2703	6	-0.5	25μm
8108-40.1	363	143	0.406	212	7	4.49E-05	1.77E-05	0.00078	0.11142	0.00105	13.453	0.154	0.5242	0.0056	0.9690	0.1862	0.0005	2717	24	2708	5	-0.3	25μm
8108-72.1	61	28	0.469	38	6	2.03E-04	8.65E-05	0.00352	0.12670	0.00409	15.516	0.378	0.5453	0.0105	0.8543	0.2064	0.0026	2805	44	2877	21	2.5	25μm
8108-62.1	138	81	0.608	95	7	9.79E-05	3.53E-05	0.00170	0.17258	0.00205	16.489	0.233	0.5794	0.0070	0.9081	0.2064	0.0012	2946	29	2877	10	-2.4	25μm
8108-57.2	65	36	0.581	44	3	9.94E-05	5.97E-05	0.00172	0.15860	0.00395	16.341	0.284	0.5733	0.0086	0.9121	0.2067	0.0015	2921	35	2880	12	-1.4	25μm
8108-8.1	63	56	0.916	46	1	4.74E-05	6.93E-05	0.00082	0.25522	0.00403	16.468	0.266	0.5711	0.0075	0.8707	0.2091	0.0017	2912	31	2899	13	-0.5	25μm
8108-12.1	44	16	0.373	28	1	3.48E-05	1.53E-04	0.00060	0.10718	0.00611	16.465	0.390	0.5661	0.0094	0.7829	0.2109	0.0031	2892	39	2913	24	0.7	25μm
8108-22.1	38	17	0.464	24	3	1.40E-04	1.60E-04	0.00243	0.12991	0.00674	16.221	0.486	0.5542	0.0098	0.6834	0.2123	0.0047	2843	41	2923	36	2.7	25μm

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	$\frac{Th}{U}$	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	f(206)^{204}	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Age (Ma) $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)	spot size
Location #3 (03GRS-015)																							
Biotite tonalite gneiss																							
8107-29.1	75	25	0.337	38	44	1.44E-03	1.50E-04	0.02489	0.09985	0.00644	11.168	0.327	0.4614	0.0095	0.7807	0.1756	0.0032	2446	42	2611	31	6.4	25µm
8107-12.1	2198	116	0.055	1197	24	2.40E-05	2.43E-06	0.00042	0.01469	0.00012	13.395	0.150	0.5285	0.0057	0.9826	0.1838	0.0004	2735	24	2688	3	-1.8	25µm
8107-10.1	1009	786	0.805	625	23	5.16E-05	8.77E-06	0.00089	0.22043	0.00065	13.031	0.160	0.5122	0.0060	0.9828	0.1845	0.0004	2666	26	2694	4	1	25µm
8107-55.1	402	188	0.483	233	28	1.57E-04	2.02E-05	0.00272	0.13048	0.00114	13.061	0.149	0.5128	0.0055	0.9723	0.1847	0.0005	2669	24	2696	4	1	25µm
8107-1.1	1040	106	0.105	567	21	4.45E-05	4.54E-06	0.00077	0.02886	0.00024	13.302	0.146	0.5220	0.0056	0.9914	0.1848	0.0003	2708	24	2697	2	-0.4	25µm
8107-47.1	302	24	0.082	161	23	1.74E-04	1.72E-05	0.00301	0.02351	0.00071	13.060	0.159	0.5123	0.0057	0.9470	0.1849	0.0007	2667	24	2697	7	1.1	25µm
8107-37.1	329	30	0.093	174	19	1.32E-04	2.49E-05	0.00228	0.02644	0.00098	12.980	0.157	0.5086	0.0055	0.9404	0.1851	0.0008	2651	24	2699	7	1.8	25µm
8107-15.1	550	190	0.357	316	30	1.21E-04	1.21E-05	0.00210	0.09931	0.00067	13.283	0.150	0.5198	0.0055	0.9704	0.1854	0.0005	2698	23	2701	5	0.1	25µm
8107-4.1	623	108	0.179	327	17	6.26E-05	1.08E-05	0.00109	0.04981	0.00058	12.612	0.158	0.4933	0.0054	0.9216	0.1854	0.0009	2585	23	2702	8	4.3	25µm
8107-17.1	1093	6	0.006	600	43	8.62E-05	7.29E-06	0.00149	0.00140	0.00032	13.770	0.169	0.5371	0.0063	0.9822	0.1859	0.0004	2771	27	2707	4	-2.4	25µm
8107-19.1	684	121	0.183	373	49	1.62E-04	1.09E-05	0.00280	0.05180	0.00052	13.166	0.150	0.5123	0.0054	0.9579	0.1864	0.0006	2667	23	2711	5	1.6	25µm
8107-16.1	276	192	0.720	169	10	3.29E-04	3.11E-05	0.00569	0.20391	0.00161	13.181	0.170	0.5126	0.0059	0.9340	0.1865	0.0009	2668	25	2711	8	1.6	25µm
8107-62.1	89	11	0.127	48	22	5.45E-04	5.86E-05	0.00945	0.04032	0.00270	13.206	0.203	0.5118	0.0060	0.8369	0.1871	0.0016	2664	26	2717	14	1.9	25µm
8107-2.1	487	281	0.596	296	21	9.81E-05	1.18E-05	0.00170	0.16638	0.00120	13.493	0.153	0.5212	0.0056	0.9764	0.1878	0.0005	2704	24	2723	4	0.7	25µm
8107-27.1	196	192	1.014	127	16	1.86E-04	2.98E-05	0.00323	0.28260	0.00176	13.286	0.162	0.5121	0.0056	0.9428	0.1882	0.0008	2666	24	2726	7	2.2	25µm
8107-5.1	239	179	0.776	142	22	2.17E-04	2.37E-05	0.00375	0.23638	0.00192	12.733	0.173	0.4862	0.0056	0.9044	0.1899	0.0011	2554	24	2742	10	6.8	25µm
Location #4 (03GRS-016)																							
Biotite tonalite to granodiorite																							
8106-1.1	251	212	0.872	162	11	1.01E-04	2.79E-05	0.00174	0.24166	0.00212	13.457	0.190	0.5221	0.0060	0.8727	0.1869	0.0013	2708	25	2715	11	0.3	25µm
8106-2.1	259	194	0.773	172	321	2.54E-03	9.70E-05	0.04408	0.23695	0.00419	13.843	0.247	0.5426	0.0058	0.6946	0.1850	0.0024	2794	24	2699	21	-3.5	25µm
8106-3.1	244	177	0.750	153	9	8.07E-05	3.03E-05	0.00140	0.20299	0.00179	13.443	0.165	0.5220	0.0057	0.9322	0.1868	0.0008	2707	24	2714	7	0.2	25µm
8106-5.1	229	190	0.861	149	2	2.15E-05	1.63E-05	0.00037	0.23497	0.00205	13.769	0.183	0.5323	0.0059	0.8910	0.1876	0.0011	2751	25	2721	10	-1.1	25µm
8106-4.1	126	144	1.180	86	4	6.57E-05	4.14E-05	0.00114	0.32755	0.00322	13.643	0.218	0.5243	0.0063	0.8230	0.1887	0.0017	2718	27	2731	15	0.5	25µm
8106-6.1	217	53	0.253	123	9	8.89E-05	2.42E-05	0.00154	0.06618	0.00134	13.422	0.242	0.5236	0.0072	0.8288	0.1859	0.0019	2714	30	2706	17	-0.3	25µm
8106-7.1	191	174	0.939	124	6	6.45E-05	2.76E-05	0.00112	0.26264	0.00278	13.448	0.192	0.5214	0.0062	0.8884	0.1871	0.0012	2705	26	2716	11	0.4	25µm
8106-16.1	269	197	0.757	171	1	6.49E-06	1.31E-05	0.00011	0.21000	0.00177	13.707	0.181	0.5284	0.0060	0.9122	0.1882	0.0010	2735	25	2726	9	-0.3	25µm
8106-19.1	226	207	0.946	145	42	4.16E-04	5.26E-05	0.00722	0.24569	0.00331	13.175	0.192	0.5224	0.0058	0.8268	0.1829	0.0015	2709	24	2679	14	-1.1	25µm
8106-31.1	324	240	0.763	205	11	7.28E-05	1.99E-05	0.00126	0.20742	0.00142	13.559	0.168	0.5266	0.0059	0.9428	0.1868	0.0008	2727	25	2714	7	-0.5	25µm
8106-33.1	653	658	1.042	437	3	8.51E-06	5.07E-06	0.00015	0.28349	0.00129	13.566	0.172	0.5288	0.0056	0.8936	0.1861	0.0011	2736	24	2708	9	-1	25µm
8106-41.1	211	188	0.921	135	4	4.01E-05	2.41E-05	0.00069	0.25418	0.00195	13.409	0.198	0.5166	0.0068	0.9374	0.1882	0.0010	2685	29	2727	9	1.5	25µm
8106-45.1	104	99	0.979	68	7	1.52E-04	4.15E-05	0.00263	0.27027	0.00294	13.383	0.212	0.5214	0.0071	0.9136	0.1862	0.0012	2705	30	2708	11	0.1	25µm
8106-46.1	1595	77	0.050	886	8	1.08E-05	3.19E-06	0.00019	0.01349	0.00026	13.581	0.178	0.5400	0.0068	0.9826	0.1824	0.0005	2783	29	2675	4	-4.1	25µm
8106-46.2	351	326	0.962	227	17	1.07E-04	1.92E-05	0.00185	0.26228	0.00169	13.332	0.161	0.5177	0.0056	0.9358	0.1868	0.0008	2689	24	2714	7	0.9	25µm

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	$\frac{Th}{U}$	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	f(206)^{204}	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207*}Pb}{^{206}Pb}$	Apparent Age (Ma) $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)	spot size
Location #5 (03GRS-017)																							
Tonalite to granodiorite gneiss																							
8110-72.1	224	122	0.56	144	5	4.51E-05	1.80E-05	0.00078	0.15130	0.00357	15.103	0.191	0.5520	0.0061	0.9237	0.1985	0.0010	2833	25	2814	8	-0.7	25µm
8110-71.1	457	272	0.62	298	6	2.66E-05	9.57E-06	0.00046	0.17077	0.00107	15.120	0.172	0.5525	0.0058	0.9590	0.1985	0.0007	2835	24	2814	5	-0.8	25µm
8110-6.1	260	161	0.64	160	20	1.71E-04	4.89E-05	0.00296	0.17375	0.00229	14.230	0.182	0.5234	0.0056	0.8995	0.1972	0.0011	2713	24	2803	9	3.2	25µm
8110-7.1	314	132	0.43	192	7	4.80E-05	2.57E-05	0.00083	0.11662	0.00162	14.668	0.201	0.5433	0.0061	0.8824	0.1958	0.0013	2797	26	2792	11	-0.2	25µm
8110-12.1	348	210	0.62	220	8	4.76E-05	1.62E-05	0.00083	0.17271	0.00166	14.674	0.177	0.5361	0.0057	0.9291	0.1985	0.0009	2767	24	2814	7	1.7	25µm
8110-11.1	242	101	0.43	147	6	5.55E-05	1.97E-05	0.00096	0.11910	0.00188	14.745	0.178	0.5365	0.0058	0.9360	0.1993	0.0009	2769	24	2821	7	1.8	25µm
8110-19.1	134	57	0.44	83	6	9.05E-05	4.27E-05	0.00157	0.11950	0.00241	14.988	0.268	0.5467	0.0077	0.8525	0.1989	0.0019	2811	32	2817	15	0.2	25µm
8110-20.1	772	81	0.11	427	9	2.59E-05	9.50E-06	0.00045	0.02825	0.00078	13.725	0.157	0.5283	0.0056	0.9636	0.1884	0.0006	2734	24	2728	5	-0.2	25µm
8110-46.1	951	274	0.30	555	21	4.76E-05	1.03E-05	0.00083	0.08559	0.00070	13.954	0.164	0.5319	0.0056	0.9376	0.1903	0.0008	2750	24	2744	7	-0.2	25µm
8110-52.1	191	99	0.54	120	9	1.01E-04	3.12E-05	0.00175	0.14587	0.00220	14.867	0.222	0.5446	0.0069	0.9003	0.1980	0.0013	2803	29	2810	11	0.3	25µm
8110-56.1	570	381	0.69	378	9	3.22E-05	1.87E-05	0.00056	0.18698	0.00119	15.211	0.174	0.5564	0.0058	0.9495	0.1983	0.0007	2852	24	2812	6	-1.4	25µm
8110-58.1	346	196	0.58	223	11	6.99E-05	2.14E-05	0.00121	0.15906	0.00158	14.994	0.212	0.5515	0.0071	0.9499	0.1972	0.0009	2832	30	2803	7	-1	25µm
8110-60.1	170	85	0.52	107	4	5.56E-05	2.41E-05	0.00096	0.14163	0.00166	15.001	0.208	0.5454	0.0060	0.8645	0.1995	0.0014	2806	25	2822	11	0.6	25µm
8110-22.1	118	67	0.58	76	5	8.52E-05	4.71E-05	0.00148	0.15959	0.00254	15.115	0.213	0.5474	0.0066	0.9070	0.2003	0.0012	2814	28	2828	10	0.5	25µm
8110-32.1	247	138	0.58	159	4	3.34E-05	1.61E-05	0.00058	0.15954	0.00245	15.083	0.176	0.5499	0.0059	0.9519	0.1989	0.0007	2825	24	2817	6	-0.3	25µm
Location #6 (03GRS-019)																							
Tonalite gneiss																							
8109-46.1	395	41	0.11	211	15	8.61E-05	1.13E-05	0.00149	0.03072	0.00052	12.914	0.145	0.5128	0.0054	0.9734	0.1826	0.0005	2669	23	2677	4	0.3	25µm
8109-36.1	412	53	0.13	218	14	7.61E-05	1.07E-05	0.00132	0.03759	0.00051	12.702	0.149	0.5044	0.0056	0.9775	0.1826	0.0005	2633	24	2677	4	1.7	25µm
8109-68.1	424	80	0.19	229	23	1.25E-04	2.24E-05	0.00217	0.05727	0.00093	12.795	0.172	0.5080	0.0065	0.9745	0.1827	0.0006	2648	28	2677	5	1.1	25µm
8109-6.1	467	55	0.12	251	10	5.00E-05	8.41E-06	0.00087	0.03314	0.00042	12.961	0.154	0.5142	0.0058	0.9755	0.1828	0.0005	2674	25	2679	4	0.2	25µm
8109-39.1	396	54	0.14	215	10	5.65E-05	1.54E-05	0.00098	0.04069	0.00066	12.993	0.158	0.5150	0.0057	0.9535	0.1830	0.0007	2678	24	2680	6	0.1	25µm
8109-21.2	297	51	0.18	157	15	1.17E-04	1.79E-05	0.00203	0.05077	0.00096	12.626	0.183	0.4990	0.0068	0.9658	0.1835	0.0007	2610	29	2685	6	2.8	25µm
8109-80.1	344	48	0.15	180	37	2.52E-04	2.26E-05	0.00437	0.04244	0.00109	12.543	0.168	0.4947	0.0061	0.9611	0.1839	0.0007	2591	26	2688	6	3.6	25µm
8109-27.1	432	87	0.21	238	15	7.77E-05	1.04E-05	0.00135	0.05908	0.00081	13.080	0.143	0.5153	0.0054	0.9778	0.1841	0.0004	2679	23	2690	4	0.4	25µm
8109-54.1	451	41	0.09	243	10	4.80E-05	9.61E-06	0.00083	0.02638	0.00044	13.133	0.161	0.5168	0.0060	0.9738	0.1843	0.0005	2686	26	2692	5	0.2	25µm
8109-15.1	181	24	0.13	94	49	6.37E-04	1.41E-05	0.01105	0.03890	0.00190	12.645	0.191	0.4907	0.0067	0.9414	0.1869	0.0010	2574	29	2715	9	5.2	25µm
8109-4.1	141	53	0.39	82	11	1.74E-04	2.96E-05	0.00301	0.10925	0.00147	13.462	0.178	0.5203	0.0060	0.9220	0.1877	0.0010	2701	26	2722	9	0.8	25µm
8109-73.1	181	94	0.54	107	12	1.53E-04	2.43E-05	0.00264	0.14617	0.00189	13.357	0.174	0.5162	0.0061	0.9513	0.1877	0.0008	2683	26	2722	7	1.4	25µm
8109-1.1	1252	84	0.07	688	10	1.70E-05	3.24E-06	0.00029	0.01918	0.00017	13.736	0.157	0.5293	0.0056	0.9630	0.1882	0.0006	2738	24	2727	5	-0.4	25µm
8109-12.1	199	88	0.46	118	16	1.77E-04	3.72E-05	0.00306	0.12586	0.00192	13.637	0.190	0.5234	0.0064	0.9240	0.1890	0.0010	2714	27	2733	9	0.7	25µm
8109-13.1	169	62	0.38	98	11	1.47E-04	5.70E-05	0.00254	0.10510	0.00227	13.595	0.182	0.5214	0.0059	0.9003	0.1891	0.0011	2705	25	2734	10	1.1	25µm
8109-21.1	85	27	0.33	49	12	3.06E-04	8.25E-05	0.00530	0.09660	0.00365	13.432	0.255	0.5141	0.0077	0.8497	0.1895	0.0019	2674	33	2738	17	2.3	25µm
8109-79.1	100	52	0.53	60	16	3.60E-04	6.45E-05	0.00623	0.15046	0.00280	13.637	0.230	0.5217	0.0071	0.8682	0.1896	0.0016	2707	30	2739	14	1.2	25µm
8109-66.1	68	21	0.32	39	12	3.87E-04	9.41E-05	0.00671	0.09089	0.00374	13.644	0.251	0.5217	0.0074	0.8377	0.1897	0.0019	2706	31	2740	17	1.2	25µm
8109-58.1	80	30	0.38	47	12	3.35E-04	5.10E-05	0.00580	0.10412	0.00226	13.637	0.278	0.5209	0.0095	0.9416	0.1899	0.0013	2703	41	2741	11	1.4	25µm
8109-32.1	237	109	0.47	142	15	1.40E-04	2.41E-05	0.00243	0.13538	0.00442	13.818	0.208	0.5270	0.0070	0.9281	0.1902	0.0011	2729	30	2744	9	0.5	25µm

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	$\frac{Th}{U}$	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	f(206)^{204}	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207*}Pb}{^{206}Pb}$	Apparent Age (Ma)				Disc. (%)	spot size
																		$\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$		
Location #7 (03-GRS-008)																							
feldspar porphyritic granodiorite intruding iron formation, adjacent to basalt																							
8101-7.2	225	260	1.19	134	6	6.44E-05	1.18E-05	0.0011	0.3244	0.0030	11.671	0.149	0.4574	0.0053	0.9477	0.1851	0.0008	2428	23	2699	7	10	25µm
8101-55.1	658	218	0.34	376	23	7.85E-05	1.35E-05	0.0014	0.0932	0.0040	13.271	0.165	0.5198	0.0059	0.9577	0.1852	0.0007	2698	25	2700	6	0.1	**
8101-35.2	1190	749	0.65	739	8	1.55E-05	2.23E-06	0.0003	0.1931	0.0020	13.368	0.163	0.5232	0.0060	0.9669	0.1853	0.0006	2713	25	2701	5	-0.4	25µm
8101-19.1	71	89	1.30	48	1	4.59E-05	2.20E-05	0.0008	0.3661	0.0084	13.005	0.192	0.5089	0.0065	0.9095	0.1854	0.0012	2652	28	2701	10	1.8	25µm
8101-35.1	999	37	0.04	531	4	9.15E-06	1.71E-06	0.0002	0.0102	0.0002	13.225	0.146	0.5164	0.0056	0.9899	0.1858	0.0003	2684	24	2705	3	0.8	25µm
8101-56.2	1151	240	0.22	657	24	4.61E-05	1.15E-05	0.0008	0.0584	0.0013	13.680	0.235	0.5335	0.0071	0.8402	0.1860	0.0018	2756	30	2707	16	-1.8	**
8101-19.2	118	40	0.35	67	4	8.24E-05	2.85E-05	0.0014	0.0967	0.0026	13.310	0.196	0.5179	0.0071	0.9603	0.1864	0.0008	2690	30	2710	7	0.7	25µm
8101-4.2	830	137	0.17	465	35	9.30E-05	2.12E-05	0.0016	0.0455	0.0025	13.601	0.174	0.5291	0.0059	0.9196	0.1864	0.0009	2738	25	2711	8	-1	**
8101-7.1	325	394	1.25	223	2	1.11E-05	5.64E-06	0.0002	0.3483	0.0025	13.352	0.153	0.5189	0.0057	0.9778	0.1866	0.0005	2695	24	2713	4	0.7	25µm
8101-45.1	533	154	0.30	297	19	8.13E-05	1.48E-05	0.0014	0.0834	0.0020	13.103	0.170	0.5089	0.0061	0.9558	0.1867	0.0007	2652	26	2714	6	2.3	**
8101-59.1	331	485	1.51	235	2	1.14E-05	5.06E-06	0.0002	0.4266	0.0032	13.196	0.153	0.5113	0.0054	0.9467	0.1872	0.0007	2662	23	2718	6	2.1	25µm
8101-10.2	664	89	0.14	362	19	6.34E-05	1.43E-05	0.0011	0.0381	0.0015	13.375	0.270	0.5177	0.0075	0.7959	0.1874	0.0023	2689	32	2719	20	1.1	**
8101-85.1	118	84	0.73	73	2	4.78E-05	1.88E-05	0.0008	0.2000	0.0049	13.341	0.216	0.5156	0.0074	0.9335	0.1877	0.0011	2681	32	2722	10	1.5	25µm
8101-3.1	510	282	0.57	311	21	9.18E-05	3.09E-05	0.0016	0.1583	0.0065	13.640	0.172	0.5267	0.0060	0.9398	0.1878	0.0008	2728	25	2723	7	-0.2	**
8101-44.1	91	120	1.36	63	1	3.58E-05	2.63E-05	0.0006	0.3677	0.0052	13.456	0.207	0.5196	0.0065	0.8709	0.1878	0.0014	2697	28	2723	13	1	25µm
8101-65.1	837	252	0.31	479	23	6.26E-05	1.12E-05	0.0011	0.0858	0.0017	13.515	0.199	0.5218	0.0063	0.8768	0.1878	0.0013	2707	27	2723	12	0.6	**
8101-76.1	81	52	0.66	49	3	7.13E-05	1.74E-05	0.0012	0.1819	0.0033	13.261	0.173	0.5116	0.0060	0.947	0.1880	0.0008	2663	26	2725	7	2.3	25µm
8101-4.1	50	27	0.57	30	3	1.22E-04	4.37E-05	0.0021	0.1622	0.0045	13.607	0.222	0.5237	0.0073	0.9074	0.1885	0.0013	2715	31	2729	11	0.5	25µm
8101-20.1	88	50	0.59	51	3	7.39E-05	2.75E-05	0.0013	0.1640	0.0033	12.853	0.192	0.4946	0.0067	0.9443	0.1885	0.0009	2591	29	2729	8	5.1	25µm
8101-61.1	662	449	0.70	398	4	1.25E-05	2.73E-06	0.0002	0.1972	0.0013	13.121	0.146	0.5048	0.0052	0.9642	0.1885	0.0006	2634	22	2729	5	3.5	25µm
8101-71.1	175	86	0.51	103	3	4.28E-05	1.33E-05	0.0007	0.1415	0.0020	13.475	0.168	0.5173	0.0057	0.9245	0.1889	0.0009	2688	24	2733	8	1.7	25µm
8101-10.1	121	99	0.84	77	1	1.66E-05	1.79E-05	0.0003	0.2345	0.0039	13.556	0.183	0.5197	0.0063	0.9418	0.1892	0.0009	2698	27	2735	8	1.4	25µm
8101-70.1	223	172	0.80	140	2	2.08E-05	8.22E-06	0.0004	0.2247	0.0030	13.475	0.160	0.5163	0.0056	0.9523	0.1893	0.0007	2683	24	2736	6	1.9	25µm
8101-27.1	86	11	0.13	47	1	3.65E-05	3.24E-05	0.0006	0.0361	0.0032	13.425	0.195	0.5140	0.0061	0.8781	0.1895	0.0013	2674	26	2737	12	2.3	25µm
8101-37.1	86	37	0.45	50	3	8.21E-05	2.05E-05	0.0014	0.1213	0.0038	13.431	0.197	0.5121	0.0066	0.9298	0.1902	0.0010	2666	28	2744	9	2.9	25µm
8101-30.2	337	118	0.36	199	3	1.78E-05	7.48E-06	0.0003	0.1014	0.0016	14.100	0.193	0.5288	0.0069	0.9809	0.1934	0.0005	2736	29	2771	4	1.3	25µm
8101-30.1	282	100	0.37	167	1	7.18E-06	9.48E-06	0.0001	0.1009	0.0019	14.258	0.183	0.5303	0.0065	0.9795	0.1950	0.0005	2743	27	2785	4	1.5	25µm
Location #8 (03GRS-0030)																							
Quartz diorite																							
8102-2.1	100	66	0.68	60	1	3.40E-05	1.84E-05	0.00059	0.1937	0.0057	12.967	0.173	0.5051	0.0061	0.9460	0.18619	0.00081	2636	26	2709	7	2.7	25µm
8102-20.1	134	75	0.58	80	3	5.28E-05	2.16E-05	0.00092	0.1609	0.0027	13.230	0.165	0.5147	0.0059	0.9540	0.18644	0.00070	2676	25	2711	6	1.3	25µm
8102-31.1	122	121	1.03	80	1	1.73E-05	1.26E-05	0.00030	0.2948	0.0035	13.331	0.169	0.5154	0.0060	0.9576	0.18760	0.00069	2680	26	2721	6	1.5	25µm
8102-36.1	88	72	0.85	56	3	7.44E-05	4.48E-05	0.00129	0.2370	0.0067	13.309	0.205	0.5175	0.0069	0.9177	0.18652	0.00115	2689	30	2712	10	0.8	25µm
8102-19.1	153	125	0.84	95	2	3.46E-05	1.01E-05	0.00060	0.2353	0.0028	13.034	0.151	0.5066	0.0054	0.9588	0.18660	0.00062	2642	23	2712	5	2.6	25µm
8102-22.1	87	89	1.06	56	3	7.22E-05	2.78E-05	0.00125	0.2967	0.0063	12.957	0.196	0.5052	0.0062	0.8657	0.18600	0.00142	2636	26	2707	13	2.6	25µm
8102-37.1	131	102	0.81	80	3	4.54E-05	1.58E-05	0.00079	0.2156	0.0030	12.979	0.170	0.5038	0.0061	0.9622	0.18684	0.00067	2630	26	2715	6	3.1	25µm
8102-42.1	109	117	1.11	73	2	3.90E-05	2.32E-05	0.00068	0.3060	0.0039	13.296	0.192	0.5189	0.0067	0.9378	0.18584	0.00094	2694	28	2706	8	0.4	25µm
8102-48.1	119	98	0.85	74	2	3.92E-05	1.85E-05	0.00068	0.2345	0.0034	13.143	0.174	0.5119	0.0062	0.9469	0.18620	0.00080	2665	26	2709	7	1.6	25µm
8102-49.1	91	74	0.83	58	2	5.11E-05	2.02E-05	0.00089	0.2369	0.0039	13.237	0.195	0.5157	0.0066	0.9151	0.18617	0.00111	2681	28	2709	10	1	25µm
8102-61.1	57	39	0.70	35	3	1.26E-04	3.26E-05	0.00218	0.1940	0.0044	13.224	0.223	0.5168	0.0075	0.9109	0.18559	0.00130	2686	32	2703	12	0.7	25µm
8102-63.1	278	396	1.47	196	3	2.75E-05	1.16E-05	0.00048	0.4061	0.0031	13.161	0.147	0.5132	0.0055	0.9760	0.18600	0.00046	2670	23	2707	4	1.4	25µm
8102-72.1	121	130	1.11	81	3	5.45E-05	1.84E-05	0.00094	0.3089	0.0043	13.244	0.189	0.5161	0.0068	0.9622	0.18613	0.00073	2682	29	2708	6	1	25µm
8102-12.1	286	2	0.01	149	19	1.55E-04	2.94E-05	0.00268	0.0020	0.0014	13.127	0.217	0.5099	0.0068	0.8676	0.18670	0.00155	2656	29	2713	14	2.1	**
8102-31.2	599	40	0.07	288	38	1.61E-04	2.06E-05	0.00279	0.0196	0.0013	11.871	0.144	0.4644	0.0051	0.9462	0.18542	0.00074	2459	23	2702	7	9	**

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	$\frac{Th}{U}$	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	f(206)^{204}	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207*}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Age (Ma) $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)	spot size
Location #9 (03GRS-0028)																							
Granodiorite gneiss																							
8103-55.1	285	190	0.69	172	6	4.83E-05	8.64E-06	0.00084	0.1951	0.0020	12.796	0.141	0.5101	0.0054	0.9784	0.18194	0.00042	2657	23	2671	4	0.5	25µm
8103-1.1	588	51	0.09	328	18	6.62E-05	1.92E-05	0.00115	0.0261	0.0013	13.532	0.267	0.5360	0.0083	0.8482	0.18311	0.00193	2767	35	2681	18	-3.2	**
8103-51.1	508	32	0.06	277	16	7.07E-05	1.70E-05	0.00122	0.0209	0.0024	13.307	0.167	0.5266	0.0061	0.9581	0.18328	0.00066	2727	26	2683	6	-1.6	**
8103-2.1	591	68	0.12	324	20	7.64E-05	1.52E-05	0.00132	0.0313	0.0014	13.276	0.170	0.5251	0.0062	0.9605	0.18338	0.00066	2721	26	2684	6	-1.4	**
8103-38.1	415	79	0.20	231	11	5.85E-05	1.73E-05	0.00101	0.0547	0.0022	13.213	0.195	0.5226	0.0065	0.8949	0.18338	0.00122	2710	27	2684	11	-1	**
8103-52.1	719	66	0.09	387	5	1.61E-05	3.44E-06	0.00028	0.0260	0.0006	13.089	0.143	0.5174	0.0054	0.9797	0.18349	0.00040	2688	23	2685	4	-0.1	25µm
8103-68.1	317	55	0.18	167	4	3.12E-05	7.12E-06	0.00054	0.0526	0.0010	12.574	0.167	0.4968	0.0058	0.9269	0.18358	0.00092	2600	25	2685	8	3.2	25µm
8103-25.1	2382	252	0.11	1290	6	6.07E-06	1.28E-06	0.00011	0.0293	0.0003	13.149	0.166	0.5190	0.0063	0.9842	0.18375	0.00041	2695	27	2687	4	-0.3	25µm
8103-6.1	947	96	0.10	510	3	7.54E-06	2.00E-06	0.00013	0.0294	0.0008	13.096	0.142	0.5158	0.0053	0.9749	0.18416	0.00045	2681	23	2691	4	0.3	25µm
8103-48.1	791	48	0.06	439	31	8.46E-05	1.29E-05	0.00147	0.0157	0.0009	13.683	0.164	0.5382	0.0058	0.9463	0.18438	0.00072	2776	25	2693	6	-3.1	**
8103-63.1	1344	37	0.03	716	4	7.11E-06	1.92E-06	0.00012	0.0081	0.0003	13.214	0.144	0.5191	0.0054	0.9841	0.18462	0.00036	2695	23	2695	3	0	25µm
8103-69.1	965	12	0.01	517	5	1.25E-05	3.01E-06	0.00022	0.0032	0.0002	13.355	0.145	0.5242	0.0054	0.9797	0.18479	0.00040	2717	23	2696	4	-0.8	25µm
8103-46.1	326	34	0.11	182	20	1.37E-04	2.74E-05	0.00237	0.0286	0.0030	13.882	0.211	0.5336	0.0067	0.8806	0.18867	0.00137	2757	28	2731	12	-1	**
8103-66.1	385	61	0.17	217	5	2.82E-05	5.83E-06	0.00049	0.0521	0.0009	14.017	0.203	0.5262	0.0068	0.9359	0.19322	0.00100	2725	29	2770	8	1.6	25µm
8103-62.1	223	48	0.22	126	3	3.21E-05	1.47E-05	0.00056	0.0625	0.0018	13.981	0.176	0.5226	0.0059	0.9456	0.19402	0.00080	2710	25	2777	7	2.4	25µm
8103-13.1	55	28	0.52	33	4	1.70E-04	6.69E-05	0.00295	0.1468	0.0046	14.082	0.223	0.5259	0.0063	0.8305	0.19421	0.00173	2724	27	2778	15	1.9	25µm
8103-10.1	112	7	0.06	61	4	7.04E-05	1.82E-05	0.00122	0.0202	0.0012	13.915	0.219	0.5194	0.0072	0.9269	0.19429	0.00116	2697	31	2779	10	3	25µm
8103-19.1	249	19	0.08	139	3	2.85E-05	8.17E-06	0.00049	0.0209	0.0018	14.281	0.168	0.5329	0.0057	0.9507	0.19437	0.00072	2754	24	2780	6	0.9	25µm
8103-20.1	406	36	0.09	226	4	2.04E-05	6.79E-06	0.00035	0.0254	0.0010	14.262	0.162	0.5308	0.0057	0.9685	0.19489	0.00056	2745	24	2784	5	1.4	25µm
8103-13.2	345	35	0.11	190	28	1.77E-04	4.92E-05	0.00306	0.0272	0.0024	14.103	0.222	0.5242	0.0070	0.9052	0.19511	0.00132	2717	30	2786	11	2.5	**
8103-8.1	248	83	0.34	145	6	5.09E-05	1.09E-05	0.00088	0.0939	0.0014	14.263	0.157	0.5295	0.0055	0.9743	0.19536	0.00049	2739	23	2788	4	1.7	25µm
8103-58.1	63	37	0.60	38	3	1.07E-04	4.12E-05	0.00185	0.1726	0.0041	13.983	0.232	0.5165	0.0074	0.9193	0.19634	0.00129	2684	32	2796	11	4	25µm
8103-23.1	126	23	0.19	72	3	6.06E-05	1.67E-05	0.00105	0.0525	0.0016	14.349	0.219	0.5298	0.0067	0.8853	0.19642	0.00140	2741	28	2797	12	2	25µm
8103-50.1	323	28	0.09	180	2	1.09E-05	8.48E-06	0.00019	0.0263	0.0013	14.384	0.167	0.5310	0.0056	0.9483	0.19647	0.00073	2746	24	2797	6	1.8	25µm
8103-76.1	208	10	0.05	113	3	3.16E-05	8.76E-06	0.00055	0.0137	0.0007	14.147	0.161	0.5218	0.0056	0.9682	0.19663	0.00056	2707	24	2798	5	3.3	25µm
8103-18.1	166	75	0.47	106	3	3.53E-05	9.62E-06	0.00061	0.1291	0.0035	15.691	0.275	0.5562	0.0086	0.9247	0.20460	0.00138	2851	36	2863	11	0.4	25µm
8103-85.1	92	59	0.66	61	6	1.32E-04	2.50E-05	0.00228	0.1795	0.0033	15.831	0.277	0.5519	0.0081	0.8962	0.20806	0.00163	2833	34	2891	13	2	25µm
Location #10 (03GRS-0027)																							
Quartz Diorite																							
8104-2.1	110	88	0.83	69	5	1.04E-04	2.89E-05	0.0018	0.2253	0.0034	13.346	0.166	0.5172	0.0056	0.9210	0.18715	0.00091	2687	24	2717	8	1.1	25µm
8104-16.1	105	92	0.90	68	3	7.06E-05	1.96E-05	0.0012	0.2628	0.0037	13.557	0.172	0.5184	0.0059	0.9429	0.18965	0.00081	2693	25	2739	7	1.7	25µm
8104-18.1	153	53	0.36	88	4	5.82E-05	3.02E-05	0.0010	0.0991	0.0022	13.554	0.165	0.5202	0.0057	0.9459	0.18895	0.00075	2700	24	2733	7	1.2	25µm
8104-20.1	112	68	0.63	66	3	6.80E-05	2.42E-05	0.0012	0.1740	0.0030	13.063	0.175	0.5067	0.0055	0.8759	0.18697	0.00122	2643	24	2716	11	2.7	25µm
8104-22.1	106	66	0.65	65	3	6.37E-05	2.98E-05	0.0011	0.1776	0.0034	13.530	0.193	0.5227	0.0062	0.8887	0.18774	0.00124	2711	26	2722	11	0.4	25µm
8104-26.1	61	22	0.38	35	0	4.79E-06	2.37E-05	0.0001	0.1079	0.0030	13.342	0.187	0.5132	0.0064	0.9289	0.18855	0.00099	2670	27	2730	9	2.2	25µm
8104-33.1	82	32	0.41	46	3	8.98E-05	2.75E-05	0.0016	0.1095	0.0028	13.203	0.192	0.5068	0.0065	0.9297	0.18895	0.00102	2643	28	2733	9	3.3	25µm
8104-42.1	102	25	0.26	56	3	6.35E-05	2.36E-05	0.0011	0.0701	0.0027	13.271	0.184	0.5107	0.0062	0.9177	0.18848	0.00105	2660	26	2729	9	2.5	25µm
8104-48.1	91	68	0.77	57	3	7.31E-05	2.03E-05	0.0013	0.2187	0.0035	13.358	0.180	0.5135	0.0058	0.8981	0.18867	0.00113	2672	25	2731	10	2.2	25µm
8101-68.1	151	62	0.42	88	3	3.85E-05	1.67E-05	0.0007	0.1169	0.0032	13.469	0.167	0.5180	0.0056	0.9184	0.18860	0.00093	2691	24	2730	8	1.4	25µm
8104-67.1	724	671	0.96	479	6	1.76E-05	3.29E-06	0.0003	0.2596	0.0023	13.740	0.160	0.5310	0.0060	0.9833	0.18766	0.00040	2746	25	2722	4	-0.9	25µm
8104-79.1	112	53	0.49	66	4	8.07E-05	1.65E-05	0.0014	0.1306	0.0040	13.392	0.181	0.5182	0.0061	0.9207	0.18742	0.00100	2692	26	2720	9	1	25µm
8104-87.1	159	149	0.97	103	5	6.53E-05	1.40E-05	0.0011	0.2819	0.0032	13.431	0.188	0.5125	0.0066	0.9543	0.19006	0.00080	2667	28	2743	7	2.7	25µm

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb (ppb)	$^{204}Pb/^{206}Pb$	$\pm\,^{204}Pb/^{206}Pb$	$f(206)^{204}$	$^{208*}Pb/^{206*}Pb$	$\pm\,^{208}Pb/^{206}Pb$	$^{207*}Pb/^{235}U$	$\pm\,^{207}Pb/^{235}U$	$^{206*}Pb/^{238}U$	$\pm\,^{206}Pb/^{238}U$	Corr Coeff	$^{207*}Pb/^{206*}Pb$	$\pm\,^{207}Pb/^{206}Pb$	Apparent Age (Ma)				Disc (%)	spot size
																		$^{206}Pb/^{238}U$	$\pm\,^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$\pm\,^{207}Pb/^{206}Pb$		
Location # 11 (04GRS-02B)																							
Intermediate volcanic																							
8223-22.1	76	53	0.72	48	1	2.82E-05	3.64E-05	0.00049	0.19557	0.00248	13.84394	0.23154	0.52787	0.00754	0.9071	0.19021	0.00135	2732	32	2744	12	0.4	25µm
8223-2.1	85	49	0.59	52	4	1.01E-04	2.85E-05	0.00175	0.15724	0.00386	13.64537	0.21163	0.52912	0.00679	0.8856	0.18704	0.00136	2738	29	2716	12	-0.8	25µm
8223-5.1	96	40	0.44	56	3	7.62E-05	2.95E-05	0.00132	0.11523	0.00175	13.49518	0.19517	0.51958	0.00604	0.8669	0.18838	0.00137	2697	26	2728	12	1.1	25µm
8223-6.1	107	61	0.59	66	3	6.77E-05	2.56E-05	0.00117	0.1607	0.00265	13.81774	0.19278	0.52803	0.00631	0.9087	0.18979	0.00111	2733	27	2740	10	0.3	25µm
8223-11.1	48	20	0.43	28	3	1.22E-04	4.76E-05	0.00212	0.11833	0.00293	13.67187	0.22716	0.52257	0.00709	0.8775	0.18975	0.00152	2710	30	2740	13	1.1	25µm
8223-13.1	47	19	0.42	27	3	1.55E-04	7.27E-05	0.00269	0.11064	0.00343	13.23612	0.32447	0.51116	0.01027	0.8707	0.1878	0.00221	2662	44	2723	19	2.3	25µm
8223-14.1	96	55	0.60	60	2	3.80E-05	2.87E-05	0.00066	0.16042	0.00192	14.01418	0.18313	0.53491	0.00611	0.9223	0.19002	0.00097	2762	26	2742	8	-0.7	25µm
8223-17.1	181	97	0.56	111	2	2.01E-05	2.07E-05	0.00035	0.14827	0.00198	13.9161	0.18759	0.53224	0.00587	0.8779	0.18963	0.00123	2751	25	2739	11	-0.4	25µm
8223-21.1	57	29	0.53	31	3	1.41E-04	8.21E-05	0.00245	0.149	0.00372	12.24398	0.21359	0.47261	0.00668	0.7884	0.18789	0.00232	2495	29	2724	20	8.4	25µm
8223-20.1	84	34	0.42	49	20	5.22E-04	1.12E-04	0.00905	0.10292	0.00192	13.61897	0.24729	0.52696	0.00685	0.7925	0.18744	0.00209	2729	29	2720	19	-0.3	25µm
8223-18.1	62	20	0.33	34	4	1.42E-04	6.33E-05	0.00246	0.08731	0.0028	12.91906	0.20734	0.49156	0.00623	0.8555	0.19061	0.0016	2577	27	2747	14	6.2	25µm
8223-16.1	82	54	0.68	53	10	2.49E-04	7.34E-05	0.00431	0.18774	0.00522	14.40316	0.25534	0.54208	0.00785	0.8773	0.19271	0.00165	2792	33	2765	14	-1	25µm
8223-12.1	52	32	0.63	32	3	1.46E-04	1.05E-04	0.00253	0.16935	0.00456	13.65068	0.2745	0.5284	0.00734	0.7711	0.18737	0.00242	2735	31	2719	21	-0.6	25µm
8223-9.1	137	115	0.86	88	5	8.58E-05	2.40E-05	0.00149	0.17992	0.00575	14.18715	0.55589	0.54144	0.01483	0.7781	0.19004	0.00471	2789	62	2743	41	-1.7	25µm
Location #12 (03GRS-022)																							
quartz rich arenite grit with clay/silt at Precambrian-basement contact with Phanerozoic units																							
8221-80.1	217	78	0.373	122	8	8.14E-05	3.51E-05	0.00141	0.10199	0.00206	12.677	0.202	0.5072	0.0070	0.9130	0.1813	0.0012	2645	30	2664	11	0.7	25µm
8221-5.1	397	100	0.260	218	5	2.81E-05	1.43E-05	0.00049	0.07033	0.00090	12.839	0.164	0.5107	0.0058	0.9305	0.1823	0.0009	2660	25	2674	8	0.5	25µm
8221-32.1	229	78	0.354	131	3	3.14E-05	1.96E-05	0.00054	0.09789	0.00133	13.015	0.165	0.5177	0.0057	0.9207	0.1823	0.0009	2689	24	2674	8	-0.6	25µm
8221-19.1	215	81	0.388	122	1	9.49E-06	2.44E-05	0.00016	0.10881	0.00151	12.857	0.199	0.5105	0.0058	0.8106	0.1827	0.0017	2659	25	2677	15	0.7	25µm
8221-25.1	261	72	0.287	143	4	3.29E-05	1.93E-05	0.00057	0.07797	0.00174	12.712	0.175	0.5047	0.0058	0.8843	0.1827	0.0012	2634	25	2677	11	1.6	25µm
8221-70.1	224	115	0.533	130	2	2.38E-05	1.53E-05	0.00041	0.14802	0.00149	12.749	0.164	0.5057	0.0058	0.9319	0.1828	0.0009	2638	25	2679	8	1.5	25µm
8221-43.1	188	41	0.225	98	3	3.67E-05	2.67E-05	0.00064	0.05649	0.00149	12.312	0.161	0.4877	0.0056	0.9263	0.1831	0.0009	2560	24	2681	8	4.5	25µm
8221-69.1	170	52	0.315	93	3	3.71E-05	1.61E-05	0.00064	0.08525	0.00286	12.675	0.153	0.5013	0.0054	0.9349	0.1834	0.0008	2619	23	2684	7	2.4	25µm
8221-30.1	193	56	0.301	100	1	1.71E-05	4.16E-05	0.00030	0.08421	0.00192	12.014	0.161	0.4743	0.0053	0.8927	0.1837	0.0011	2502	23	2687	10	6.9	25µm
8221-100.1	277	94	0.349	157	3	2.55E-05	3.61E-05	0.00044	0.09483	0.00167	13.039	0.167	0.5145	0.0056	0.9087	0.1838	0.0010	2676	24	2687	9	0.4	25µm
8221-2.1	229	62	0.278	126	4	3.73E-05	2.52E-05	0.00065	0.07753	0.00134	12.906	0.180	0.5061	0.0055	0.8435	0.1850	0.0014	2640	24	2698	13	2.1	25µm
8221-47.1	101	48	0.495	59	3	7.79E-05	4.13E-05	0.00135	0.13596	0.00443	13.152	0.191	0.5155	0.0063	0.8940	0.1851	0.0012	2680	27	2699	11	0.7	25µm
8221-107.1	34	14	0.414	20	7	4.40E-04	1.75E-04	0.00762	0.10709	0.00727	13.081	0.365	0.5099	0.0098	0.7708	0.1861	0.0033	2656	42	2708	30	1.9	25µm
8221-11.1	58	38	0.672	35	4	1.62E-04	1.76E-04	0.00280	0.17476	0.00909	12.989	0.369	0.5058	0.0091	0.7170	0.1863	0.0037	2639	39	2709	33	2.6	25µm
8221-13.1	45	19	0.446	26	3	1.46E-04	1.17E-04	0.00253	0.11758	0.00519	13.410	0.274	0.5220	0.0074	0.7779	0.1863	0.0024	2708	32	2710	21	0.1	25µm
8221-72.1	12	9	0.723	8	5	9.41E-04	3.30E-04	0.01631	0.18557	0.01418	13.518	0.563	0.5262	0.0103	0.5717	0.1863	0.0064	2726	44	2710	58	-0.6	25µm
8221-39.1	85	45	0.542	51	6	1.67E-04	5.51E-05	0.00289	0.14867	0.00419	13.308	0.196	0.5177	0.0060	0.8517	0.1864	0.0015	2690	25	2711	13	0.8	25µm
8221-61.1	57	27	0.485	33	4	1.72E-04	1.05E-04	0.00298	0.12967	0.00471	13.118	0.250	0.5088	0.0066	0.7595	0.1870	0.0023	2651	28	2716	21	2.4	25µm
8221-71.1	108	43	0.412	62	2	3.26E-05	4.19E-05	0.00056	0.11210	0.00296	13.311	0.251	0.5148	0.0083	0.9066	0.1875	0.0015	2677	35	2721	13	1.6	25µm
8221-16.1	49	22	0.464	28	2	7.97E-05	9.58E-05	0.00138	0.12909	0.00447	13.080	0.260	0.5049	0.0065	0.7352	0.1879	0.0026	2635	28	2724	23	3.3	25µm
8221-4.1	46	27	0.595	27	4	1.90E-04	8.76E-05	0.00330	0.15928	0.00457	13.066	0.243	0.5043	0.0067	0.7883	0.1879	0.0022	2632	29	2724	19	3.4	25µm
8221-43.2	40	18	0.479	23	0	2.40E-05	8.96E-05	0.00042	0.13874	0.00462	12.924	0.315	0.4986	0.0100	0.8790	0.1880	0.0022	2608	43	2725	19	4.3	25µm
8221-24.1	175	85	0.501	104	0	2.79E-06	1.86E-05	0.00005	0.13850	0.00185	13.475	0.229	0.5186	0.0074	0.8925	0.1885	0.0015	2693	31	2729	13	1.3	25µm
8221-18.1	31	10	0.341	18	5	3.60E-04	2.53E-04	0.00623	0.08953	0.00999	13.212	0.387	0.5083	0.0075	0.6034	0.1885	0.0044	2649	32	2729	39	2.9	25µm
8221-21.1	94	35	0.379	55	3	6.16E-05	4.17E-05	0.00107	0.10715	0.00260	13.674	0.208	0.5247	0.0067	0.8938	0.1890	0.0013	2719	28	2733	11	0.5	25µm
8221-45.1	53	26	0.513	31	2	9.86E-05	7.13E-05	0.00171	0.14869	0.00392	13.527	0.279	0.5176	0.0084	0.8551	0.1895	0.0020	2689	36	2738	18	1.8	25µm
8221-87.1	69	37	0.553	38	1	5.08E-05	6.70E-05	0.00088	0.12182	0.00361	12.667	0.291	0.4844	0.0079	0.7896	0.1897	0.0027	2546	35	2739	24	7.1	25µm
8221-67.1	25	10	0.431	14	2	1.85E-04	2.18E-04	0.00321	0.12720	0.00896	13.144	0.426	0.5011	0.0097	0.6858	0.1902	0.0045	2619	42	2744	40	4.6	25µm
8221-10.1	54	41	0.791	33	1	4.02E-05	1.23E-04	0.00070	0.22020	0.00744	13.343	0.293	0.5076	0.0077	0.7691	0.1907	0.0027	2646	33	2748	23	3.7	25µm
8221-6.1	47	35	0.760	29	4	1.98E-04	8.74E-05	0.00343	0.21035	0.00603	13.591	0.259	0.5150	0.0073	0.8128	0.1914	0.0021	2678	31	2754	18	2.8	25µm
8221-31.1	41	13	0.334	24	2	9.18E-05	1.24E-04	0.00159	0.09764	0.00526	13.889	0.309	0.5252	0.0086	0.8066	0.1918	0.0025	2721	36	2758	22	1.3	25µm
8221-99.1	101	55	0.567	58	0	1.00E-05	1.00E-05	0.00017	0.12779	0.00236	13.430	0.263	0.5041	0.0075	0.8329	0.1932	0.0021	2631	32	2770	18	5	25µm

Table 10.1. continued

Spot name	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb (ppb)	$\frac{^{204}Pb}{^{206}Pb}$	$\pm\frac{^{204}Pb}{^{206}Pb}$	f(206)^{204}	$\frac{^{208*}Pb}{^{206*}Pb}$	$\pm\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207*}Pb}{^{235}U}$	$\pm\frac{^{207}Pb}{^{235}U}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	Corr Coeff	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Age (Ma) $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)	spot size
Location #13 (03GRS-0026)																							
quartz rich grit at Precambrian/Paleozoic contact																							
8222-66.1	41	35	0.88	26	5	2.71E-04	1.15E-04	0.0047	0.2421	0.0062	12.640	0.307	0.5047	0.0072	0.6786	0.1816	0.0033	2634	31	2668	30	1.3	25µm
8222-70.1	52	69	1.37	36	5	1.94E-04	8.53E-05	0.0034	0.3647	0.0059	13.121	0.291	0.5237	0.0093	0.8641	0.1817	0.0020	2715	39	2669	19	-1.7	25µm
8222-62.1	49	84	1.78	37	4	1.85E-04	8.94E-05	0.0032	0.4860	0.0133	13.238	0.270	0.5220	0.0082	0.8414	0.1839	0.0020	2708	35	2689	18	-0.7	25µm
8222-81.1	87	102	1.21	59	6	1.53E-04	7.88E-05	0.0027	0.3336	0.0053	13.187	0.274	0.5176	0.0077	0.7895	0.1848	0.0024	2689	33	2696	21	0.3	25µm
8222-5.1	191	259	1.40	132	9	1.03E-04	9.93E-05	0.0018	0.3913	0.0059	12.952	0.209	0.5079	0.0061	0.8136	0.1850	0.0018	2648	26	2698	16	1.9	25µm
8222-12.1	146	204	1.45	101	3	4.76E-05	5.71E-05	0.0008	0.4012	0.0070	12.941	0.210	0.5070	0.0063	0.8332	0.1851	0.0017	2644	27	2699	15	2.1	25µm
8222-32.1	178	171	0.99	115	7	9.07E-05	4.34E-05	0.0016	0.2712	0.0030	13.080	0.226	0.5122	0.0063	0.7884	0.1852	0.0020	2666	27	2700	18	1.3	25µm
8222-20.1	71	75	1.09	47	2	6.23E-05	1.22E-04	0.0011	0.3070	0.0061	13.055	0.292	0.5111	0.0082	0.7929	0.1852	0.0025	2662	35	2700	23	1.4	25µm
8222-33.1	74	97	1.36	51	6	1.85E-04	7.93E-05	0.0032	0.3837	0.0052	13.024	0.220	0.5089	0.0063	0.8065	0.1856	0.0019	2652	27	2704	17	1.9	25µm
8222-71.1	77	120	1.62	54	7	2.18E-04	1.25E-04	0.0038	0.4435	0.0123	12.782	0.294	0.4993	0.0083	0.8018	0.1857	0.0026	2611	36	2704	23	3.5	25µm
8222-22.1	157	106	0.70	96	6	8.18E-05	3.97E-05	0.0014	0.1896	0.0028	13.229	0.189	0.5163	0.0057	0.8462	0.1858	0.0014	2684	24	2706	13	0.8	25µm
8222-8.1	162	87	0.55	96	5	7.28E-05	2.38E-05	0.0013	0.1492	0.0019	13.237	0.221	0.5165	0.0063	0.8051	0.1859	0.0019	2684	27	2706	17	0.8	25µm
8222-41.1	47	59	1.28	32	6	2.73E-04	1.20E-04	0.0047	0.3547	0.0066	13.123	0.300	0.5120	0.0069	0.6782	0.1859	0.0032	2665	29	2706	28	1.5	25µm
8222-65.1	112	23	0.21	62	3	6.01E-05	3.55E-05	0.0010	0.0590	0.0026	13.306	0.231	0.5186	0.0079	0.9289	0.1861	0.0012	2693	34	2708	11	0.5	25µm
8222-28.1	60	50	0.87	37	0	1.00E-05	1.00E-05	0.0002	0.2421	0.0036	13.044	0.250	0.5076	0.0071	0.8018	0.1864	0.0022	2646	30	2710	19	2.4	25µm
8222-37.1	55	85	1.61	40	4	1.55E-04	9.78E-05	0.0027	0.4490	0.0135	13.354	0.246	0.5196	0.0068	0.7857	0.1864	0.0021	2698	29	2710	19	0.5	25µm
8222-85.1	90	198	2.28	73	2	4.54E-05	3.98E-05	0.0008	0.6263	0.0075	13.348	0.206	0.5183	0.0065	0.8704	0.1868	0.0014	2692	28	2714	13	0.8	25µm
8222-64.1	91	43	0.49	52	3	8.51E-05	5.50E-05	0.0015	0.1341	0.0034	12.996	0.287	0.5041	0.0084	0.8273	0.1870	0.0023	2631	36	2716	21	3.1	25µm
8222-9.1	97	105	1.12	64	1	2.62E-05	1.12E-04	0.0005	0.3172	0.0052	13.120	0.231	0.5088	0.0061	0.7661	0.1870	0.0021	2651	26	2716	19	2.4	25µm
8222-15.1	59	108	1.90	43	3	1.15E-04	7.09E-05	0.0020	0.5147	0.0086	12.973	0.336	0.5030	0.0095	0.803	0.1871	0.0029	2627	41	2717	26	3.3	25µm
8222-76.1	267	79	0.31	149	6	5.12E-05	1.77E-05	0.0009	0.0810	0.0012	13.185	0.195	0.5109	0.0066	0.9209	0.1872	0.0011	2661	28	2717	10	2.1	25µm
8222-19.1	188	181	0.99	122	1	9.86E-06	2.01E-05	0.0002	0.2702	0.0038	13.404	0.210	0.5193	0.0066	0.8714	0.1872	0.0015	2696	28	2718	13	0.8	25µm
8222-24.1	47	88	1.91	36	1	4.68E-05	1.15E-04	0.0008	0.5199	0.0093	13.252	0.367	0.5131	0.0098	0.7688	0.1873	0.0033	2670	42	2719	30	1.8	25µm
8222-17.1	83	55	0.69	51	1	3.72E-05	4.14E-05	0.0006	0.1915	0.0039	13.396	0.236	0.5181	0.0074	0.875	0.1875	0.0016	2691	32	2721	14	1.1	25µm
8222-68.1	111	58	0.54	66	6	1.25E-04	4.48E-05	0.0022	0.1481	0.0026	13.306	0.203	0.5132	0.0066	0.9015	0.1881	0.0013	2670	28	2725	11	2	25µm
8222-3.1	177	90	0.52	104	0	5.40E-06	6.08E-05	0.0001	0.1419	0.0027	13.363	0.194	0.5148	0.0059	0.8534	0.1883	0.0014	2677	25	2727	13	1.8	25µm
8222-54.1	200	51	0.26	114	3	3.29E-05	4.37E-05	0.0006	0.0701	0.0020	13.653	0.201	0.5257	0.0067	0.9156	0.1884	0.0011	2723	28	2728	10	0.2	25µm
8222-75.1	87	51	0.61	51	2	4.20E-05	5.34E-05	0.0007	0.1729	0.0039	13.118	0.280	0.5043	0.0084	0.843	0.1887	0.0022	2632	36	2730	19	3.6	25µm
8222-38.1	78	64	0.85	49	3	9.36E-05	5.66E-05	0.0016	0.2400	0.0074	13.300	0.293	0.5111	0.0081	0.7995	0.1888	0.0025	2661	35	2731	22	2.6	25µm
8222-87.1	90	50	0.57	53	4	1.05E-04	5.41E-05	0.0018	0.1566	0.0030	13.362	0.197	0.5126	0.0061	0.8644	0.1890	0.0014	2668	26	2734	12	2.4	25µm
8222-69.1	160	98	0.63	100	3	4.05E-05	5.58E-05	0.0007	0.1810	0.0032	13.863	0.211	0.5282	0.0065	0.8727	0.1904	0.0014	2734	28	2745	12	0.4	25µm

Notes (see Stern, 1997)

Uncertainties reported at 1s (absolute) and are calculated by numerical propagation of all known sources of error

f206^{204} refers to mole fraction of total 206Pb that is due to common Pb, calculated using the 204Pb-method; common Pb composition used is the surface blank

* refers to radiogenic Pb (corrected for common Pb)

Discordance relative to origin = 100 * (1-(206Pb/238U age)/(207Pb/206Pb age))

** Indicates that a 17 µm spot size was used. Unless otherwise noted, a 25µm spot was used

Table 10.2. Samarium-neodymium (Sm/Nd) isotopic values. Model ages are based on DePaolo (1981).

Location Number	Sample Number	Age, Ga (SHRIMP)	Age Error	[Nd] (ppm) (1)	[Sm] (ppm) (1)	^{147}Sm/^{144}Nd (1)	2σ (1)	^{143}Nd/^{144}Nd (2)	2σ (2)	ε^{143}Nd (3)	2σ (4)	TDM (Ma)
1	03-GRS-013	2.73	0.01	51.84	8.18	0.09533	0.00016	0.510854	0.000013	0.83	0.30	2841
2	03-GRS-14	2.70	0.01	15.76	3.13	0.12015	0.00014	0.511276	0.000013	0.03	0.28	2910
3	03-GRS-15	2.70	0.01	11.39	2.25	0.11938	0.00013	0.511307	0.000014	0.91	0.30	2832
5	03-GRS-17	2.81	0.01	24.21	4.20	0.10483	0.00015	0.511021	0.000014	1.70	0.31	2856
6	03-GRS-19	2.68	0.01	14.31	1.88	0.07941	0.00009	0.510609	0.000013	0.89	0.30	2781
7	03-GRS-008	2.73	0.01	20.19	4.07	0.12200	0.00015	0.511206	0.000014	−1.69	0.29	3095
8	03-GRS-0030	2.71	0.01	69.33	10.13	0.08832	0.00023	0.510824	0.000013	2.44	0.30	2714
9	03-GRS-28	2.69	0.01	7.96	1.66	0.12590	0.00013	0.511364	0.000014	−0.34	0.30	2949
10	03-GRS-27	2.73	0.01	28.27	4.71	0.10067	0.00014	0.510981	0.000013	1.44	0.29	2802
11	04-GRS-2B	2.74	0.01	9.09	1.73	0.11485	0.00012	0.511215	0.000013	1.13	0.28	2844

1) Sm and Nd concentrations and ^{147}Sm/^{144}Nd ratios are corrected for blank of 2±2 pg for both Sm and Nd. The uncertainty is propagated into the error of ^{147}Sm/^{144}Nd ratio.

2) Nd isotopic ratios are corrected for fractionation relative to the ratio of ^{146}Nd/^{144}Nd=0.7219, using exponential law and real atomic masses. The ^{143}Nd/^{144}Nd isotopic ratios are adjusted to ^{143}Nd/^{144}Nd=0.51186 in the La Jolla standard.

3) ε^{143}Nd at the time indicated in the column "Age, Ga" relative to the accepted Chondritic Uniform Reservoir with ^{143}Nd/^{144}Nd=0.512636 and ^{147}Sm/^{144}Nd=0.1966.

4) Uncertainty in ε^{143}Nd is propagated to include uncertainties in age, ^{143}Nd/^{144}Nd, and ^{147}Sm/^{144}Nd.

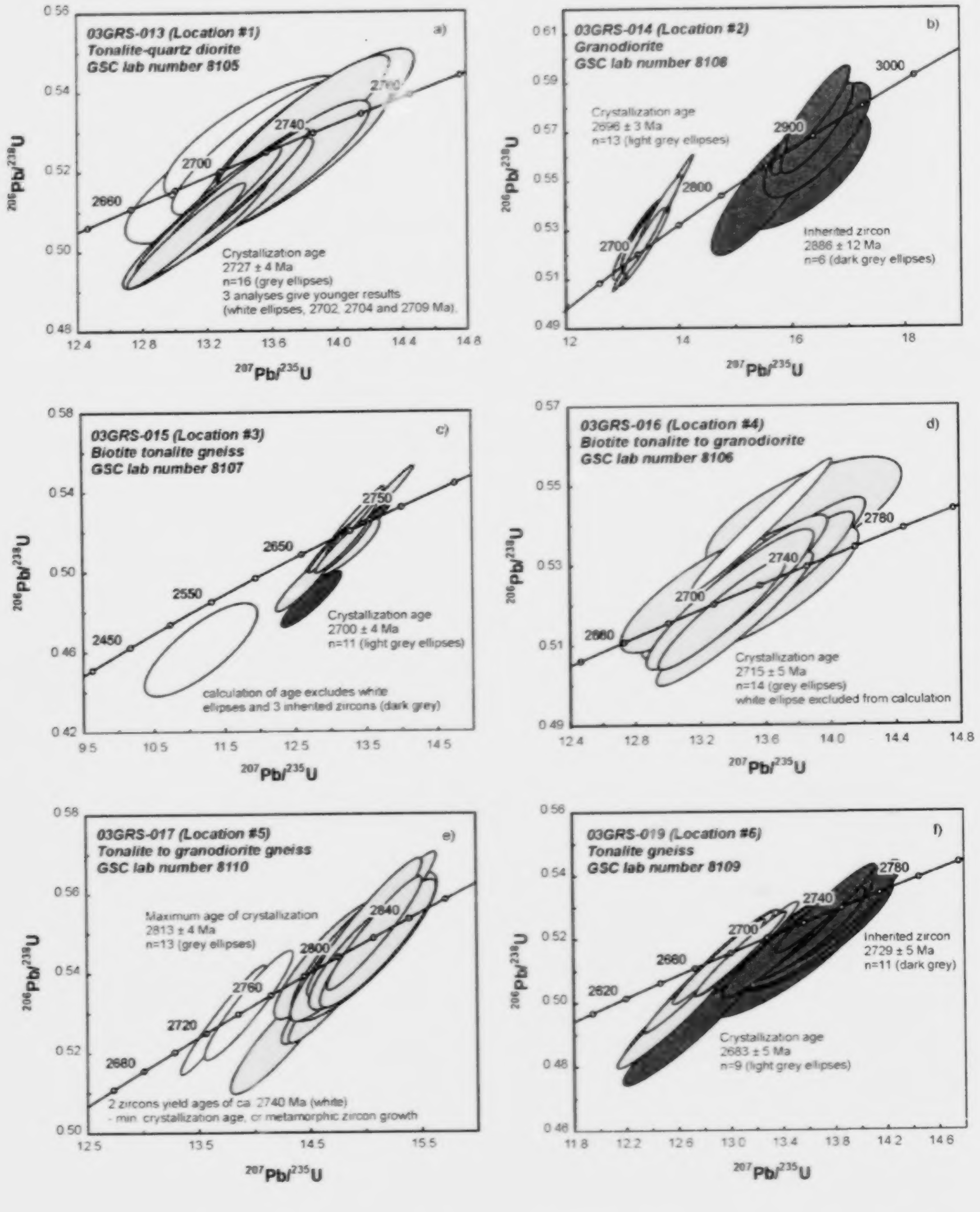


Figure 10.3. Concordia diagrams of U/Pb zircon results from exposed basement samples. Data-point error ellipses are 2σ. Location # refers to location shown on Figure 10.2. See text for discussion.

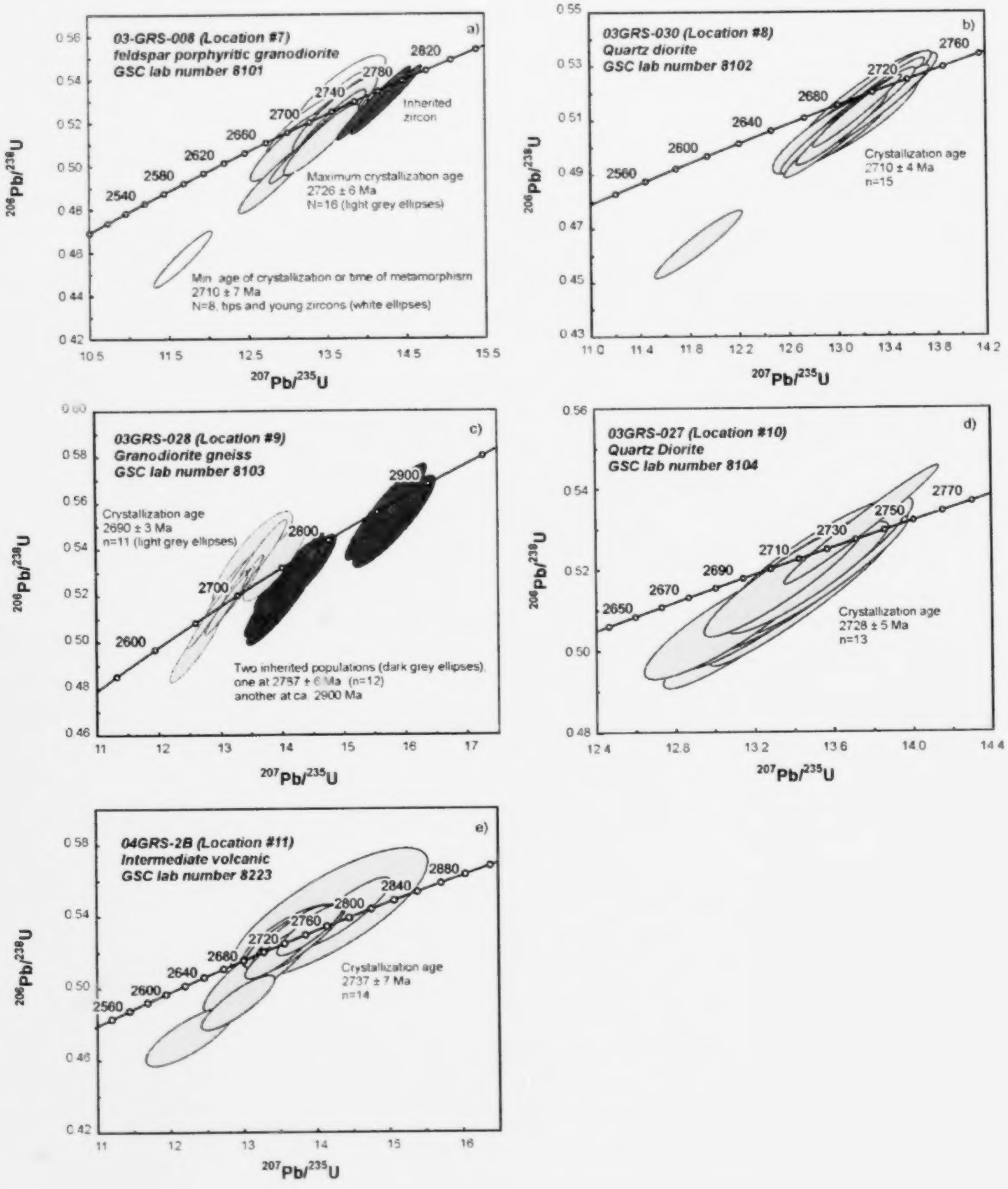


Figure 10.4. Concordia diagrams of U/Pb zircon results from drill core basement samples. Data-point error ellipses are 2σ. Location # refers to locations shown in Figure 10.2. See text for discussion.

Location 5. Sample 03GRS-017 is a tonalite to granodiorite gneiss. Zircons are mostly low U, with faint oscillatory zones. Thirteen analyses (13 different zircons) give a weighted mean $^{207}Pb/^{206}Pb$ age of 2813±4 Ma (grey ellipses on Figure 10.3e, MSWD = 1.01, probability of fit = 44%). Two analyses (white ellipses, grains #20 and #46) yielded much younger results (2728 and 2744 Ma, respectively). It was not possible to reproduce the younger ages in any of the other zircons. These results could be interpreted two ways. The younger zircon could be interpreted as a minimum crystallization age with the 2.8 Ga zircon representing an inherited or xenocrystic component. Alternately, the younger zircon could be metamorphic in origin, making the 2.8 Ga age the igneous age. The younger zircons do not have physical features that would help to interpret their ages, however, one possible clue to the origin of the younger zircon may lie in their chemistry. The younger zircons have elevated U content relative to the 2.8 Ga zircon (~800 ppm versus 100–500 ppm) and slightly lower Th/U (0.11–0.30 versus 0.43–0.64): a characteristic that is consistent with metamorphic zircon. For this reason, our preferred interpretation of the result is crystallization at 2813 Ma with later metamorphic zircon growth at 2730 to 2740 Ma.

Location 6. Sample 03GRS-019 is a tonalite gneiss. Zircons are composed of high U, faintly zoned or unzoned rims around low U, oscillatory zoned cores. Nine analyses of the high U zircon (9 different zircon grains) give a weighted mean age of 2683±3 Ma (light grey ellipses on Figure 10.3f, MSWD = 1.8, probability of fit = 7%). This is interpreted as the time of crystallization. The cores give a weighted mean $^{207}Pb/^{206}Pb$ age of 2729±5 Ma (dark grey ellipses, MSWD = 1.01, probability of fit = 44%), which is interpreted as the age of inherited or xenocrystic material.

Basement Samples: Drill Core

Location 7. Sample 03GRS-008 is a feldspar-porphyritic granodiorite intruding iron formation, adjacent to basalt. Zircons are composed of high U, fine oscillatory-zoned rims around low U, broad oscillatory zoned cores. There are also zircons solely composed of either the high U or low U material. The mean $^{207}Pb/^{206}Pb$ age of eight analyses from high U zircon is 2710±7 Ma (white ellipses on concordia diagram, Figure 10.4a). This age constrains the minimum time of crystallization or may represent an episode of metamorphism. The mean $^{207}Pb/^{206}Pb$ age of the low U zircon is 2726±6 Ma (n=16, light grey ellipses). The oscillatory zoning evident in the low U zircon indicates growth of zircon from magma. Therefore, this result constrains a maximum age for crystallization of the granodiorite. Two analyses on one zircon gives an age of circa 2780 Ma (dark grey ellipses), which clearly represents an inherited or xenocrystic component.

Location 8. Sample 03GRS-0030 is a quartz diorite. Fifteen analyses of 14 different zircon grains give a weighted mean $^{207}Pb/^{206}Pb$ age of 2710±4 Ma (grey ellipses on Figure 10.4b, MSWD = 0.51, probability of fit = 93%). This is interpreted as the time of crystallization. There is no evidence from the results, or any indication in the images of the zircons, of any older inherited cores. The zircons are diffusely zoned (straight zoning, oscillatory zoning, occasional irregular zoning).

Location 9. Sample 03GRS-0028 is a granodiorite gneiss. Zircons are composed of high U, fine-oscillatory zoned rims around low U, diffusely zoned cores. Eleven analyses of the high U zircon (11 different zircon grains) give a weighted mean age of 2690±3 Ma (light grey ellipses on Figure 10.4c, MSWD = 1.17, probability of fit = 30%). This is interpreted as the time of crystallization. The ages of the cores fall into two groups. Twelve zircons give a weighted mean $^{207}Pb/^{206}Pb$ age of 2787±6 Ma, and two others yield ages of circa 2.9 Ga. These zircons are interpreted as inherited or xenocrystic.

Location 10. Sample 03GRS-0027 is a quartz diorite. Thirteen analyses of 13 different zircon grains give a weighted mean $^{207}Pb/^{206}Pb$ age of 2728±5 Ma (grey ellipses on Figure 10.4d, MSWD = 1.3, probability of fit 22%). This is interpreted as the time of crystallization. There is no evidence from the results or any indication in the images of the zircons of any older inherited cores. The zircons are euhedral prisms with well-developed oscillatory zoning.

Location 11. Sample 04GRS-2B is an intermediate volcanic. Zircon recovery from this zircon was quite poor; only 20 zircon grains were extracted. Fourteen analyses of 14 different zircon grains give a weighted mean $^{207}Pb/^{206}Pb$ age of 2737±7 Ma (grey ellipses on Figure 10.4e, MSWD = 0.9, probability of fit = 56%). This is interpreted as the time of crystallization. There is no evidence from the results, or any indication in the images of the zircons, of any older inherited cores. The zircons are diffusely zoned (straight zoning, oscillatory zoning, occasional irregular zoning).

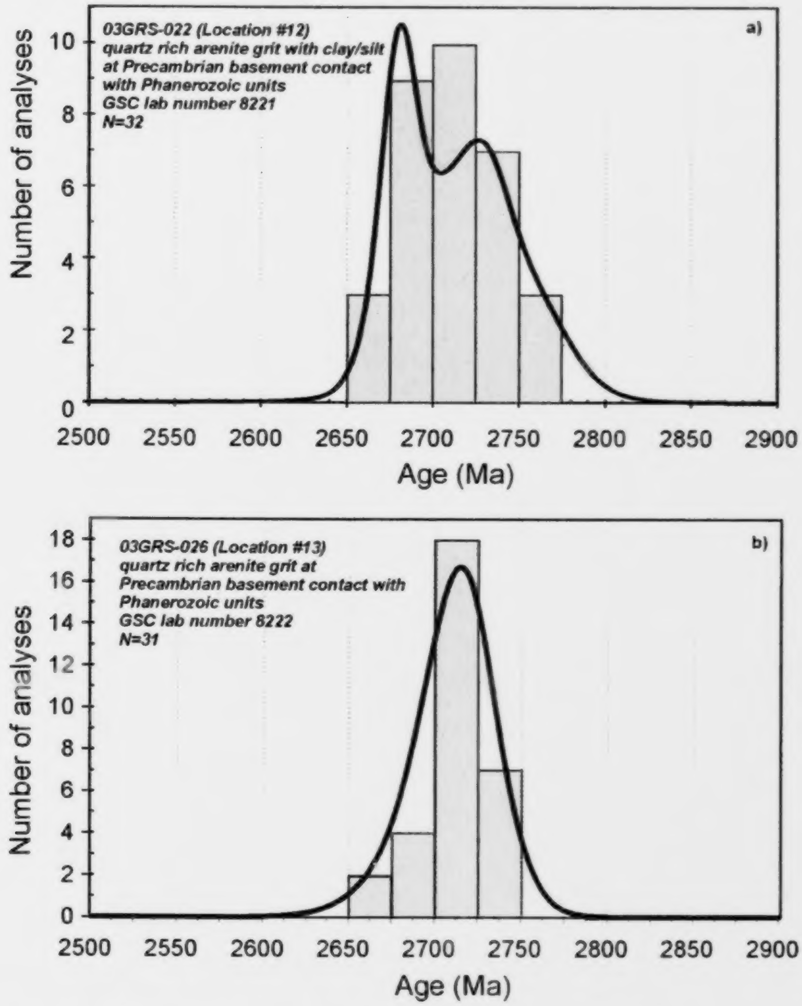


Figure 10.5. Cumulative probability diagrams with histograms of U/Pb detrital zircon results from basal sedimentary samples. All data are greater than 93% concordant. Chosen bin width (25 Ma) results in 50% efficiency (Sircombe 2004). Location # refers to locations shown in Figure 10.2. See text for discussion.

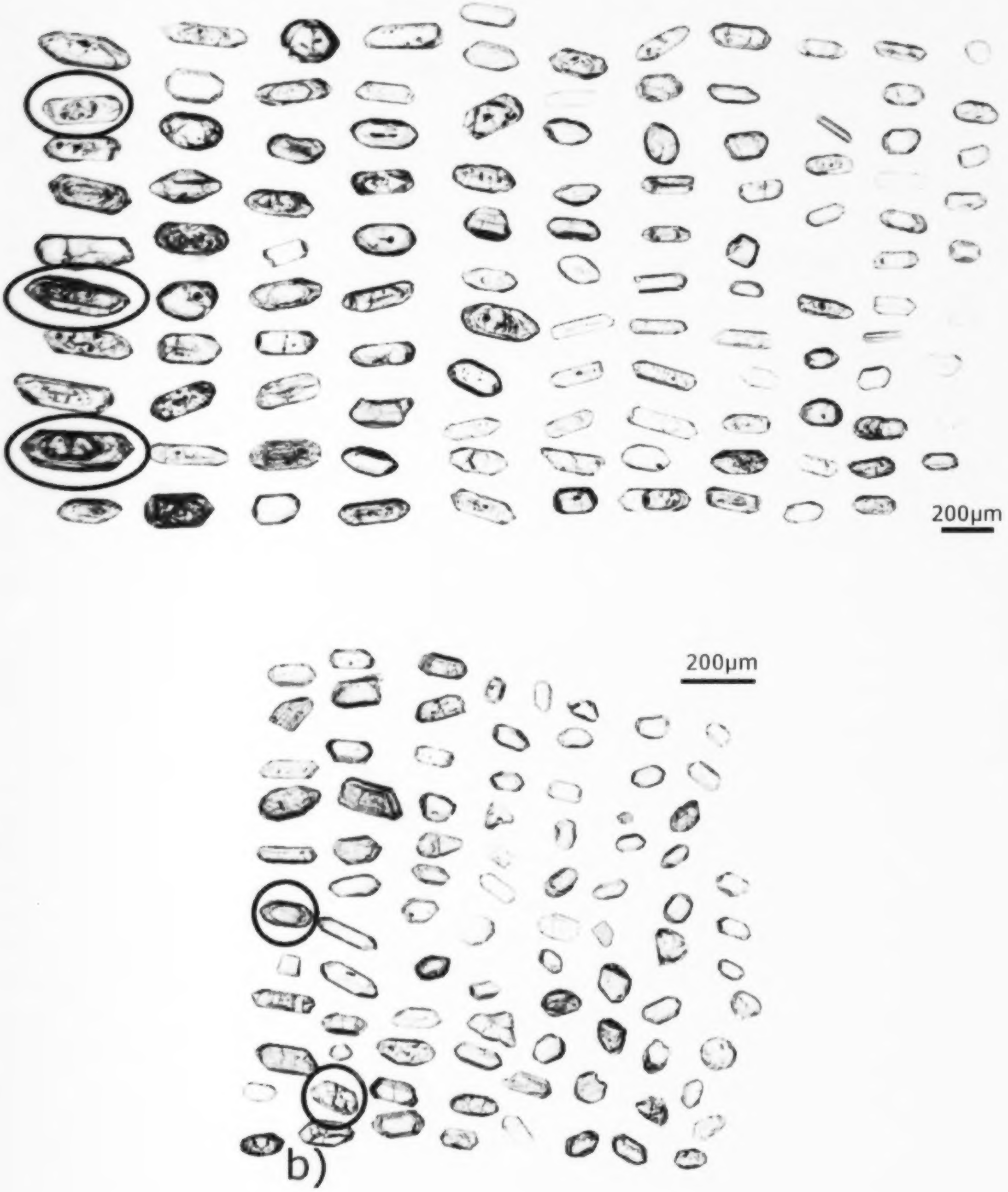


Figure 10.6. Transmitted light images of zircons illustrating the appearance and layout of a typical SHRIMP zircon sample: **a)** Detrital zircons from sample 03GRS-022 (location 12 on Figure 10.2), a quartz-rich arenite grit with clay and silt at the Archean basement contact with Paleozoic strata. The site is near the Attawapiskat River, just south of the Victor kimberlite pipe of De Beers Canada Exploration Inc.; **b)** Zircons from plutonic sample 03GRS-008 (location 7 on Figure 10.2), a feldspar porphyritic granodiorite intruding iron formation within a basaltic unit of a narrow folded greenstone belt under the Hudson Bay Lowlands. Note the core and overgrowth relationships in the circled grains.

Post-Archean Sedimentary Samples

Location 12. Sample 03GSR-022 is a quartz-rich arenite grit with clay and silt at the Archean basement contact with the Phanerozoic units. Approximately 120 zircons were mounted and imaged, of which a subset of 31 were analyzed. The data are presented as a cumulative probability curve overlain by a histogram (Figure 10.5a). The $^{207}Pb/^{206}Pb$ ages of the zircons range from 2664 to 2770 Ma. The results do not form a single statistical population. Two modes are evident in the cumulative probability curve, one at 2685 Ma and another at 2700 Ma although this pattern is less evident in the histogram. Regardless of the specific distribution of ages, it is clear that all zircon detritus from this rock is locally sourced from the Superior Province.

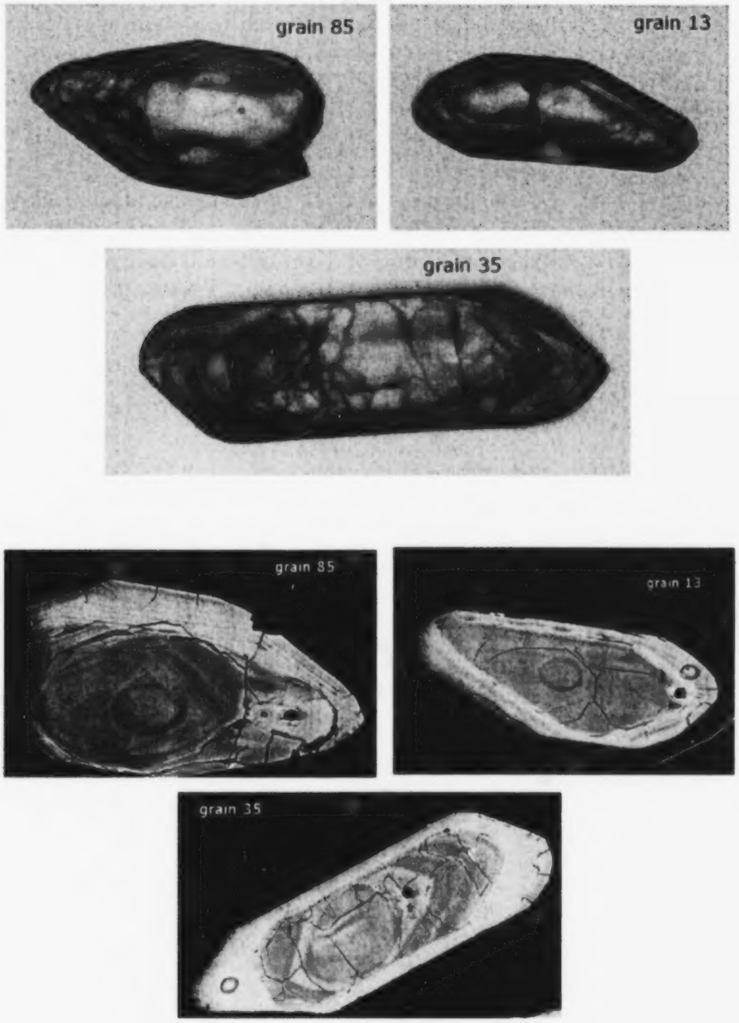


Figure 10.7. Examples of zircons imaged from sample 03GRS-028 (location 9 on Figure 10.2), which exhibit complex internal features. The elliptical depressions are sites of SHRIMP analyses. See text for details.

Post-Archean Sedimentary Samples

Location 12. Sample 03GSR-022 is a quartz-rich arenite grit with clay and silt at the Archean basement contact with the Phanerozoic units. Approximately 120 zircons were mounted and imaged, of which a subset of 31 were analyzed. The data are presented as a cumulative probability curve overlain by a histogram (Figure 10.5a). The ^{207}Pb/^{206}Pb ages of the zircons range from 2664 to 2770 Ma. The results do not form a single statistical population. Two modes are evident in the cumulative probability curve, one at 2685 Ma and another at 2700 Ma although this pattern is less evident in the histogram. Regardless of the specific distribution of ages, it is clear that all zircon detritus from this rock is locally sourced from the Superior Province.

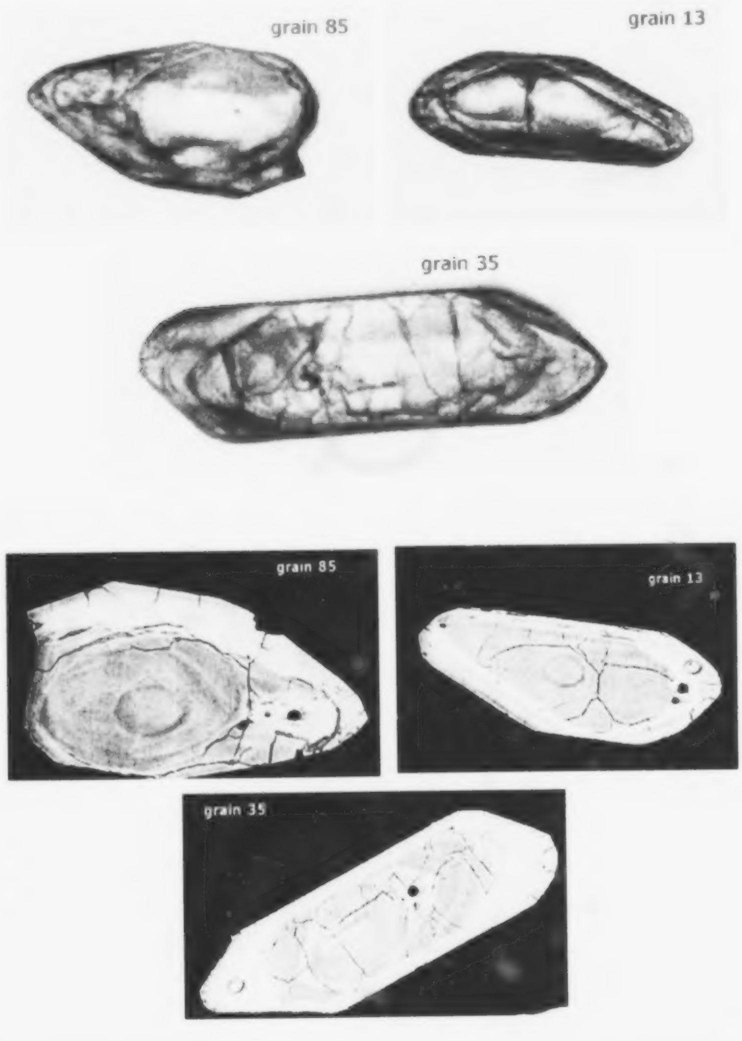


Figure 10.7. Examples of zircons imaged from sample 03GRS-028 (location 9 on Figure 10.2), which exhibit complex internal features. The elliptical depressions are sites of SHRIMP analyses. See text for details.

Location 13. Sample 03GSR-026 is a quartz-rich grit at the Archean–Paleozoic contact. Ninety zircons were mounted and imaged, of which a subset of 31 were analyzed. The data are presented in as a cumulative probability curve overlain by a histogram (Figure 10.5b). The $^{207}Pb/^{206}Pb$ ages of the zircons range from 2668 to 2745 Ma. The results form a single statistical population with a Gaussian distribution centred at 2715 Ma. From these results, it appears that this basal grit of post-Archean sediments is locally sourced.

DISCUSSION

Geological and geophysical constraints on the mechanisms for tectonic growth of the Superior Province are progressively summarized in Williams, Stott and Thurston (1992), Stott (1997) and Percival (2005), the latter based on Lithoprobe and Natmap research activities in northwestern Ontario and Manitoba since 1997. This increased knowledge encourages subdivision of the Superior Province into domains, terranes and superterranes (*sensu lato*) of contrasting tectonostratigraphic history. Progress during the Lithoprobe program in the northern Superior Province across the Ontario–Manitoba border (e.g., Skulski et al. 2000; Stone 2005) has confirmed, through mapping, geochronology and isotopic surveys, the presence of major crustal-scale boundaries at the North Kenyon fault, separating the Northern Superior superterrane and Oxford–Stull terrane, and the Stull–Wunnummin fault zone separating the North Caribou superterrane and Oxford–Stull terrane. The Island Lake domain was recognized for many years in Manitoba, but, more recently, it was merged with the Munro Lake domain and extended across Manitoba and Ontario by Parks et al. (2004). This revised Island Lake domain appears to extend across Ontario forming the northern part of the North Caribou superterrane. Based on the aeromagnetic patterns and mix of Meso- and Neoarchean volcanic ages, we have further interpreted this domain to lie between Island Lake and Stull Lake and trend eastward between North Caribou belt and Wunnummin Lake (*see* Figure 10.1). Our reconnaissance transect of granitoid and felsic volcanic age determinations and isotopic analyses, within and just west of the James Bay Lowlands, provides further constraints on the probable eastward extension most particularly of the Oxford–Stull terrane. It is now apparent that a broad Neoarchean, Oxford–Stull terrane contains crustal magmatic ages ranging from 2680 to 2740 Ma, and separates two major superterranes to the north and south, each of which contains Nd isotopic, inheritance or magmatic age evidence of > 3.0 Ga history. Furthermore, we tentatively suggest that the eastern Oxford–Stull terrane might be subdivided into at least two Neoarchean domains, with magmatic ages ranging from 2725 to 2740 Ma across the discontinuous chain of Kasabonika–McFaulds–Wunnummin greenstone belts in the south half, and ages ranging from 2680 to 2725 Ma in the north half in a domain that appears to narrow eastward under the James Bay Lowlands, based on the aeromagnetic patterns of greenstone belts (Ontario Geological Survey 2003).

The Sm/Nd tracer results (*see* Figure 10.2; *see* Table 10.2) confirm that the broad crustal area, the Oxford–Stull terrane, between the North Kenyon fault and the eastward extension of the Wunnummin greenstone belt is relatively juvenile (ε_{Nd} 0.8 to 2.4) and gives Neoarchean crystallization ages of granitoids ranging from 2690 to 2740 Ma. This is consistent with results obtained by Skulski et al. (2000) that define the north and south limits of the Oxford–Stull terrane where it straddles the Manitoba–Ontario border. Two samples of granodiorite gneiss show some evidence of slightly greater crustal contamination at location 2 (*see* Figure 10.2), near the South Kenyon fault, and location 9, near the interpreted southern margin of the Oxford–Stull terrane, with ε_{Nd} values of 0.03 and –0.34, respectively. The most dramatic change appears on the north side of the North Kenyon fault at location 7, where an ε_{Nd} value of –1.69 was obtained from a feldspar porphyritic granodiorite dike, of 2726 Ma age, cutting iron formation within amphibolitic basalt that forms a narrow, folded greenstone belt close to the Winisk fault. The model age of 3.1 Ga compares with the results of Skulski et al. (2000) farther west across the Ontario–Manitoba border and confirms the existence of a crustal block, north of the Oxford–Stull terrane, containing evidence of crustal contamination from older, pre 3.0 Ga sources.

The overall result of these U/Pb zircon SHRIMP and Sm/Nd tracer analyses supports our suspicion that the Oxford–Stull terrane continues eastward under the James Bay Lowlands, south of the North Kenyon fault, where it merges with the Winisk fault along the Attawapiskat River. A terrane boundary is postulated to pass along the Wunnummin greenstone belt based on previous observations on this belt (e.g., Stott and Janes 1985), an apparent tectonic discontinuity within the belt from aeromagnetic evidence (e.g., Gupta 1991), a major 2 km wide dextral shear zone along the northern margin of this belt, several late tectonic mafic to ultramafic intrusions along the length of the belt and the presence of carbonatite intrusions near the belt. A largely monomictic conglomeratic unit on Wunnummin Lake is dominated by pebble to boulder clasts of a granitoid rock and this sediment contains Mesoarchean detrital zircons with an age of 2965±1 Ma (Davis 1989), tentatively implying terrane uplift at this collision boundary preserved within this relatively late sedimentary unit. This terrane boundary trends along the eastward extension of the Wunnummin greenstone belt and accompanying mafic to ultramafic intrusions (*see* Figure 10.1) and appears to separate that part of the North Caribou superterrane, which might comprise an extension of the Island Lake domain, from the southern flank of the Oxford–Stull terrane. The presence of a Mesoarchean Nd model age (location 9, *see* Figure 10.2), near the eastward extension of this boundary, indicates the presence of an older crustal component, which could have been derived from northward subduction of Mesoarchean crust of the North Caribou superterrane under the Oxford–Stull terrane (as shown in Figure 10.1). Although the Oxford–Stull terrane extends eastward and under the James Bay Lowlands, the northern and southern margins of this terrane can only be roughly defined at present.

Quartz-rich arenite beds lie unconformably above the Archean basement and below the Paleozoic limestone strata at locations 12 and 13 (*see* Figure 10.2). Both sites showed similar Neoarchean ranges of zircon ages, generally from 2660 to 2770 Ma. At location 13 (*see* Figure 10.2), this seems to confirm the general absence of Meso- to Paleoarchean magmatic ages (as summarized by Stone (2005) and Skulski et al. (2000)) in the Northern Superior superterrane, which has been defined thus far largely on the presence of Meso- and Paleoarchean zircon inheritance ages and pre 3.0 Ga Nd model ages (Skulski et al. 2000).

Since virtually all significant Cu-Zn volcanogenic massive sulphide (VMS) deposits in the Superior Province are Neoarchean in age, the presence of Oxford–Stull terrane bears some importance for exploration. A Neoarchean age of 2737±7 Ma has been determined for a felsic volcanic host of recently discovered Cu-Zn volcanic-hosted massive sulphide deposits in the McFaulds Lake area, inside the edge of the James Bay Lowlands (location 11, *see* Figure 10.2). This argues for the potential of a chain of VMS occurrences to be explored along a Neoarchean tectonic assemblage extending from Kasabonika to the McFaulds Lake area, comparable to the VMS-rich assemblage along the discontinuous Shebandowan–Terrace Bay–Manitouwadge greenstone belt of the Wawa Subprovince, as described by Stott and Rayner (2004).

ACKNOWLEDGMENTS

We thank several exploration companies for their assistance in obtaining rock samples from the Sachigo Subprovince and Hudson Bay Lowlands. In particular, we thank Don Boucher and his staff of De Beers Canada Exploration Inc., Doug Hunter of Wallbridge Mining Co. Ltd. and Neil Novak and James Burns of Spider Resources Inc. This is Geological Survey of Canada Earth Science Sector Contribution number 2005348.

REFERENCES

Card, K.D. and Ciesielski, A. 1986. Subdivisions of the Superior Province of the Canadian Shield; Geoscience Canada, v.13, p.5-13.

Davis, D.W. 1989. Interim report on geochronology in the Sachigo Subprovince; Jack Satterly Geochronology Laboratory, Royal Ontario Museum, Toronto, Ontario, 11p.

DePaolo, D.J. 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic; Nature, v.291, p.193-196.

Gupta, V.K. 1991. Shaded image of total magnetic field of Ontario, northern sheet; Ontario Geological Survey, Map 2584, scale 1:1 000 000.

Ludwig, K.R. 2003. User's manual for Isoplot/Ex rev. 3.00: a geochronological toolkit for Microsoft® Excel; University of California–Berkeley, Berkeley, California, Berkeley Geochronology Center, Special Publication 4, 70p.

Ontario Geological Survey 2003. Ontario airborne geophysical surveys, magnetic data, Attawapiskat area; Ontario Geological Survey, Geophysical Data Set 1211.

Parks, J., Lin, S., Davis, D.W. and Corkery, M.T. 2004. Multiple episodes of volcanism in the Island Lake greenstone belt: evidence for a volcanic "megasequence" and implications for the extent of the North Caribou craton in the northwestern Superior Province; *in* LITHOPROBE Celebratory Conference Oral and Poster Presentations, LITHOPROBE Secretariat, University of British Columbia, Vancouver, British Columbia, E-Publication no.5, CD v.2.

Percival, J.A. 2005. The ancient Earth: development of the Canadian Shield, the oldest parts of North America – building a continental foundation from 4000 to 2500 million years ago; *in* LITHOPROBE Celebratory Conference Oral and Poster Presentations, LITHOPROBE Secretariat, University of British Columbia, Vancouver, British Columbia, E-Publication No.5, v.1.

Sircombe, K.N. 2004. AgeDisplay; an Excel workbook to evaluate and display univariate geochronological data using binned frequency histograms and probability density distributions; Computers and Geosciences, v.30, p.21-31.

Skulski, T., Corkery, M.T., Stone, D., Whalen, J.B. and Stern, R.A. 2000. Geological and geochronological investigations in the Stull Lake–Edmund Lake greenstone belt and granitoid rocks of the northwestern Superior Province; *in* Report of Activities 2000, Manitoba Industry, Trade and Mines, p.117-128.

Stern, R.A. 1997. The GSC sensitive high resolution ion microprobe (SHRIMP): analytical techniques of zircon U-Th-Pb age determinations and performance evaluation; *in* Radiogenic Age and Isotopic Studies, Report 10, Geological Survey of Canada, Current Research 1997-F, p.1-31.

Stern, R.A. and Amelin, Y. 2003. Assessment of errors in SIMS zircon U/Pb geochronology using a natural zircon standard and NIST SRM 610 glass; Chemical Geology, v.197, p.111-146.

Stone, D. 2005. Geology of the northern Superior area, Ontario; Ontario Geological Survey, Open File Report 6140, 94p.

Stott, G.M. 1997. The Superior Province, Canada; *in* Greenstone belts, Oxford Clarendon, Oxford Monograph on Geology and Geophysics 35, p.480-507.

Stott, G.M. and Janes, D.A. 1985. Reconnaissance evaluation of the Wunnummin Lake belt; *in* Summary of Field Work and Other Activities 1985, Ontario Geological Survey, Miscellaneous Paper 126, p.23-25.

Stott, G.M. and Rayner, N. 2004. Discrimination of Archean domains in the Sachigo Subprovince; *in* Summary of Field Work and Other Activities 2004; Ontario Geological Survey, Open File Report 6145, p.10-1 to 10-8.

Williams, H.R., Stott, G.M. and Thurston, P.C. 1992. Tectonic evolution of Ontario: summary and synthesis, Part 1: revolution in the Superior Province; *in* Geology of Ontario; Ontario Geological Survey, Special Volume 4, Part 2, p.1256-1294.

11. Project Unit 95-014. Geology and Soil Geochemistry of the Crooked Pine and Western Steep Rock Lakes Areas of the Wabigoon Subprovince: Implications for Gold Exploration

D. Stone[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Atikokan area of northwestern Ontario has long been recognized for having a large number of gold occurrences. Wilkinson (1982), Schnieders and Dutka (1985) and Lavigne and Scott (1995) provide detailed descriptions and overviews of numerous exposures of gold-bearing rock in the area. Some gold occurrences have been explored sporadically for over a century, whereas others have been discovered only in recent years. However, despite the abundance of gold showings coupled with small historic production and continued exploration, no gold is currently mined at Atikokan.

In recent years, regional geologic mapping was done through the central Wabigoon Subprovince, which contains the Atikokan area. Among the goals of this work was an attempt to map and describe regional geologic and structural features associated with gold mineralization in the Atikokan area. The regional mapping showed, for example, that the Sawbill, Hammond, Plator Gralouise and other gold occurrences in the western Marmion Lake area are broadly distributed along a large northeast-trending zone of sheared and altered rock—the Marmion fault (Stone, Pufahl and Carter 1995a, 1995b). However, it was impossible to visit or study all of the gold occurrences with the result that the reconnaissance mapping provided limited new information on the geologic setting of the mineralization.

During the present season, two mineralized areas east and west of Atikokan were mapped in detail to provide a level of geologic information between the property-scale descriptions of Wilkinson (1982) and Schnieders and Dutka (1985) and the reconnaissance-scale mapping. The study areas include eastern Crooked Pine Lake and western Steep Rock Lake, both of which contain several known gold occurrences. Soil sampling surveys were done concurrent with the mapping to test the usefulness of this method for exploration in the Atikokan area. The results of mapping and the available soil geochemistry are discussed below with implications for gold exploration.

REGIONAL GEOLOGIC SETTING

The Atikokan area is underlain by Archean granite and greenstone sequences comprising the Marmion terrane in the Wabigoon Subprovince of the western Superior Province. Although the western Superior Province of the Canadian Shield has historically been subdivided into easterly trending subprovinces such as the volcano-plutonic Wabigoon Subprovince, recent geochronologic and neodymium isotopic studies summarized by Tomlinson et al. (2004) have led to a revised tectonic subdivision for the area. In this classification, the Wabigoon Subprovince is subdivided into crustal blocks including the Marmion terrane, Winnipeg River terrane and Western Wabigoon terrane (Figure 11.1).

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.11-1 to 11-11.

© *Queen's Printer for Ontario 2005*

The Marmion terrane represents a block of old crustal material extending over 100 km in the Wabigoon Subprovince. The Marmion terrane includes a 3 billion-year-old basement complex (Marmion batholith) mantled by younger greenstone sequences at Lumby, Finlayson, and Steep Rock lakes and Lac des Mille Lacs (*see* Figure 11.1). Southward, granite and greenstone sequences of the Marmion terrane are in fault contact with sedimentary rocks of the Quetico Subprovince. Tectonic models (e.g., Percival and Williams 1989) maintain that the sedimentary rocks of the Quetico Subprovince represent an accretionary prism tectonically joined to the south margin of the Wabigoon Subprovince at 2.69 Ga.

GEOLOGY OF THE EASTERN CROOKED PINE LAKE AREA

The Crooked Pine Lake area is situated 40 km east of Atikokan, Ontario (*see* Figure 11.1) and straddles the boundary between the Marmion terrane of the Wabigoon Subprovince to the north and the Quetico Subprovince to the south. The area is accessible from logging roads extending north from Highway 11.

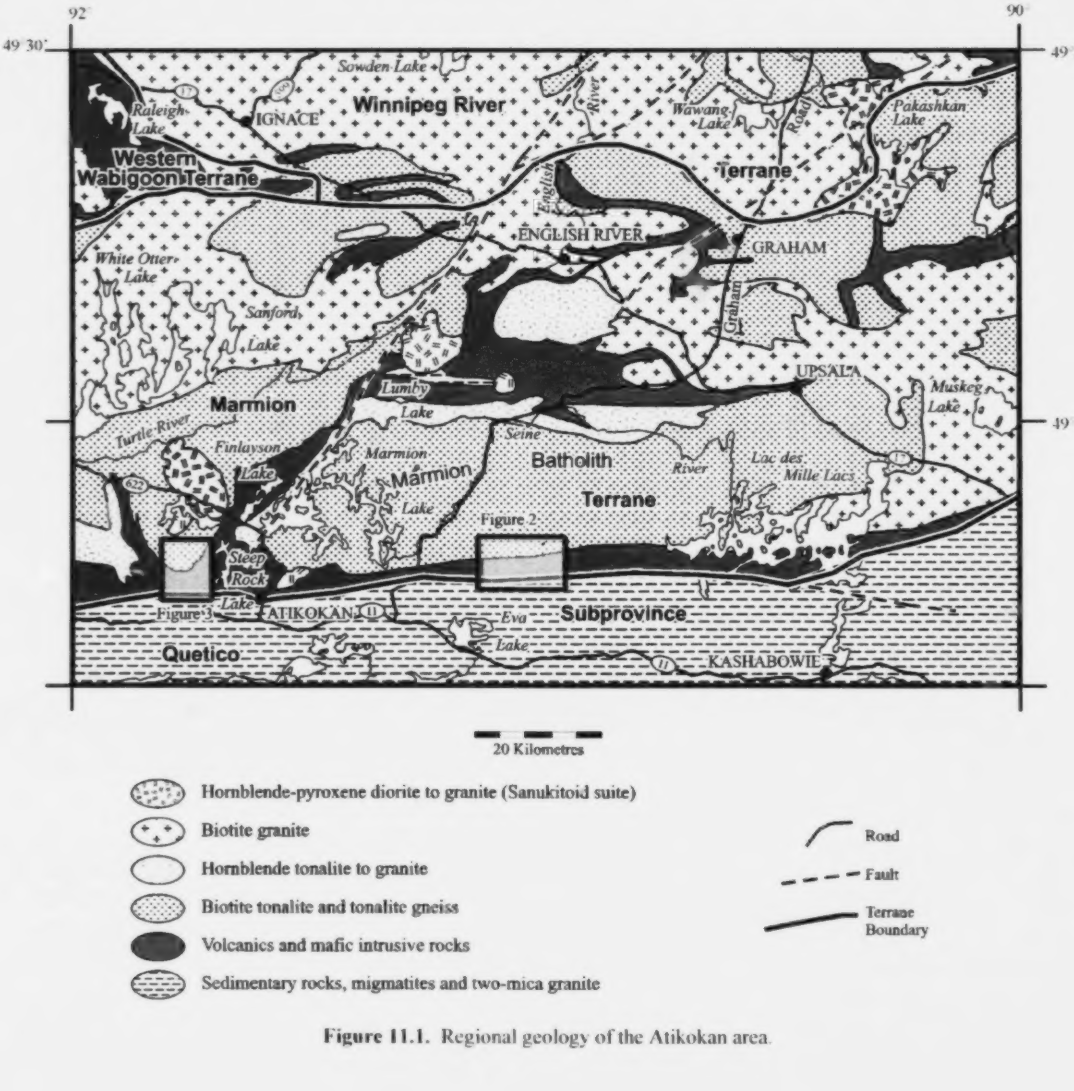

92°
90°
49°30'
49°30'
49°
Sowden Lake
Raleigh Lake
IGNACE
Winnipeg River
River
Wawang Lake
Road
Pakashkan Lake
Western Wabigoon Terrane
Terrane
English River
ENGLISH RIVER
GRAHAM
Graham
White Otter Lake
Sanford Lake
UPSALA
Muskeg Lake
Lumby Lake
Marmion
Turtle River
Finlayson Lake
Marmion Lake
Marmion
Seine
Batholith
River
Lac des Mille Lacs
Terrane
Figure 2
Steep Rock Lake
Figure 3
ATIKOKAN
Eva Lake
Subprovince
Quetico
KASHABOWIE
11
17
622
20 Kilometres
Hornblende-pyroxene diorite to granite (Sanukitoid suite)
Biotite granite
Hornblende tonalite to granite
Biotite tonalite and tonalite gneiss
Volcanics and mafic intrusive rocks
Sedimentary rocks, migmatites and two-mica granite
Road
Fault
Terrane Boundary

Figure 11.1. Regional geology of the Atikokan area.

Coarse-grained grey foliated biotite tonalite of the Marmion batholith (3.0 Ga) underlies the northern Crooked Pine Lake area (Figure 11.2). Thin strongly deformed units of clastic sedimentary rocks including arkosic sandstone and conglomerate are observed sporadically in the eastern Crooked Pine Lake area and appear to overlie the Marmion batholith. The conglomerate contains clasts of sandstone, tonalite and a coarse-grained mafic rock possibly representative of gabbro. Hard grey intermediate to felsic volcanic tuffs and breccias occur at scattered localities and probably overlie the clastic sedimentary rocks. Stone (2004) traced the intermediate to felsic volcanic rocks discontinuously eastward for 60 km to Lac des Mille Lacs and suggested that the volcanic rocks in the present area may be correlative in age with volcanic sequences (2.83 Ga) at Lac des Mille Lacs.

Gabbro dikes transect tonalite of the Marmion batholith as well as the clastic sedimentary and intermediate to felsic volcanic rocks. The gabbro dikes gradually increase in abundance south of Mercutio Lake and coalesce as a "greenstone belt" of approximately 2 km width along the north side of Crooked Pine Lake (*see* Figure 11.2). The gabbro is typically composed of medium- to coarse-grained, dark-green to black massive amphibolite. The gabbroic magma may have progressively evolved from intermediate to mafic and possibly ultramafic composition. The compositional evolution is demonstrated by early dikes of coarse-grained leucogabbro cut by late dikes of fine-grained gabbro and melagabbro. The gabbro dikes are folded and extensively fractured and are locally cut by shear zones within which the amphibole is retrogressed to an assemblage of chlorite+carbonate with associated quartz veins. Rare outcrops of dark green massive to pillowed volcanic rocks are observed within the gabbroic sequences.

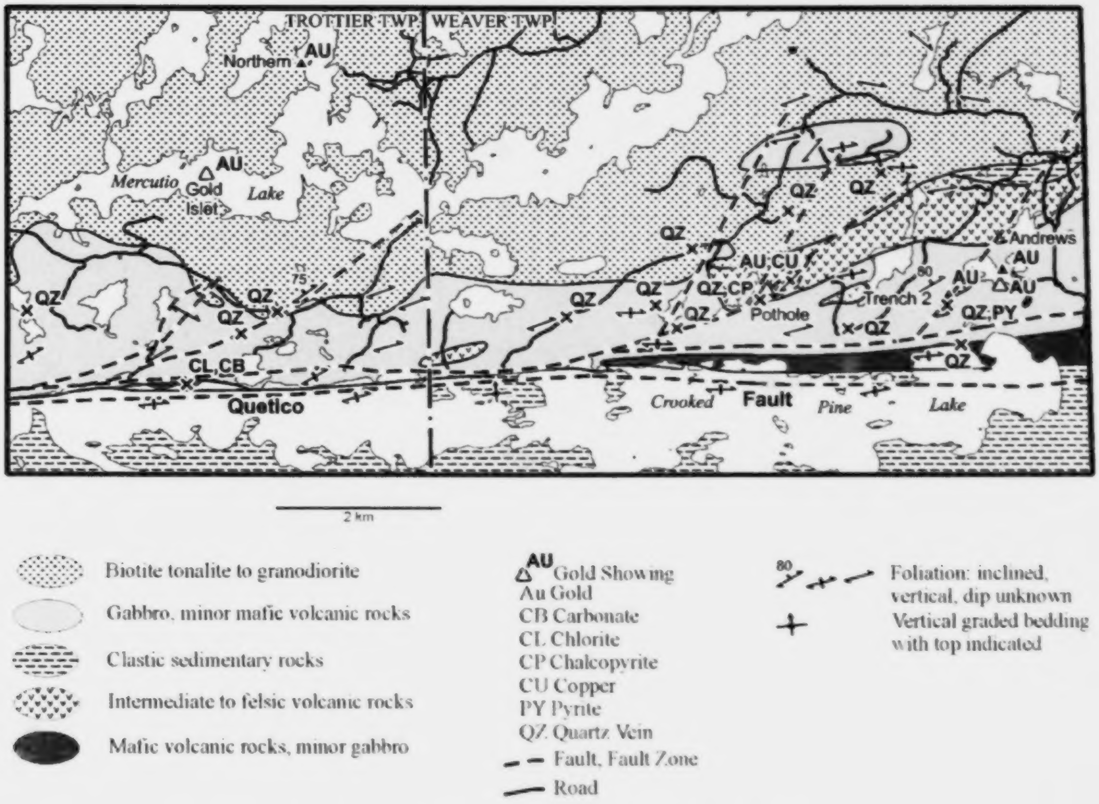

TROTTIER TWP
WEAVER TWP
Northern
AU
Mercutio
Gold Islet
Lake
AU
QZ
QZ
QZ
75
CL,CB
Quetico
QZ
QZ
QZ
QZ
AU;CU
QZ;CP
QZ
Pothole
Trench 2
80
Andrews
AU
AU
AU
QZ;PY
QZ
QZ
Crooked
Fault
Pine
Lake
2 km
Biotite tonalite to granodiorite
Gabbro, minor mafic volcanic rocks
Clastic sedimentary rocks
Intermediate to felsic volcanic rocks
Mafic volcanic rocks, minor gabbro
AU Gold Showing
Au Gold
CB Carbonate
CL Chlorite
CP Chalcopyrite
CU Copper
PY Pyrite
QZ Quartz Vein
Fault, Fault Zone
Road
80
Foliation: inclined, vertical, dip unknown
Vertical graded bedding with top indicated

Figure 11.2. Geology of the eastern Crooked Pine Lake area.

The Marmion terrane represents a block of old crustal material extending over 100 km in the Wabigoon Subprovince. The Marmion terrane includes a 3 billion-year-old basement complex (Marmion batholith) mantled by younger greenstone sequences at Lumby, Finlayson, and Steep Rock lakes and Lac des Mille Lacs (*see* Figure 11.1). Southward, granite and greenstone sequences of the Marmion terrane are in fault contact with sedimentary rocks of the Quetico Subprovince. Tectonic models (e.g., Percival and Williams 1989) maintain that the sedimentary rocks of the Quetico Subprovince represent an accretionary prism tectonically joined to the south margin of the Wabigoon Subprovince at 2.69 Ga.

GEOLOGY OF THE EASTERN CROOKED PINE LAKE AREA

The Crooked Pine Lake area is situated 40 km east of Atikokan, Ontario (*see* Figure 11.1) and straddles the boundary between the Marmion terrane of the Wabigoon Subprovince to the north and the Quetico Subprovince to the south. The area is accessible from logging roads extending north from Highway 11.

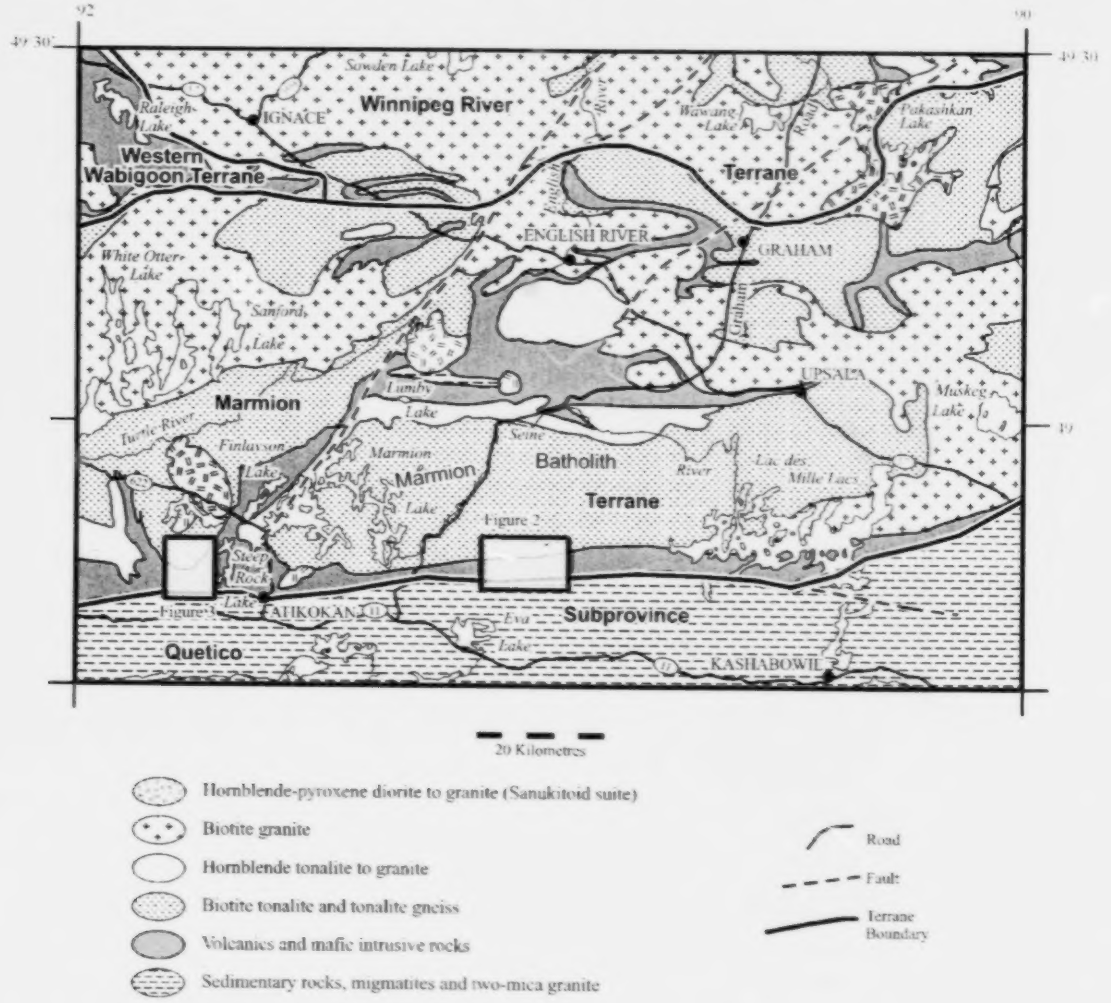

92
90
49 30'
49 30
49
Sowden Lake
Raleigh Lake
IGNACE
Winnipeg River
Western Wabigoon Terrane
English River
Wawang Lake
Road
Pakashkan Lake
Terrane
ENGLISH RIVER
GRAHAM
Graham
White Otter Lake
Sanford Lake
UPSALA
Muskeg Lake
Marmion
Lumby Lake
Turtle River
Finlayson Lake
Marmion Lake
Marmion
Seine
Batholith
River
Lac des Mille Lacs
Terrane
Figure 2
Steep Rock Lake
Figure 3
ATIKOKAN
11
Eva Lake
Subprovince
Quetico
KASHABOWIE
20 Kilometres
Hornblende-pyroxene diorite to granite (Sanukitoid suite)
Biotite granite
Hornblende tonalite to granite
Biotite tonalite and tonalite gneiss
Volcanics and mafic intrusive rocks
Sedimentary rocks, migmatites and two-mica granite
Road
Fault
Terrane Boundary

Figure 11.1. Regional geology of the Atikokan area.

Coarse-grained grey foliated biotite tonalite of the Marmion batholith (3.0 Ga) underlies the northern Crooked Pine Lake area (Figure 11.2). Thin strongly deformed units of clastic sedimentary rocks including arkosic sandstone and conglomerate are observed sporadically in the eastern Crooked Pine Lake area and appear to overlie the Marmion batholith. The conglomerate contains clasts of sandstone, tonalite and a coarse-grained mafic rock possibly representative of gabbro. Hard grey intermediate to felsic volcanic tuffs and breccias occur at scattered localities and probably overlie the clastic sedimentary rocks. Stone (2004) traced the intermediate to felsic volcanic rocks discontinuously eastward for 60 km to Lac des Mille Lacs and suggested that the volcanic rocks in the present area may be correlative in age with volcanic sequences (2.83 Ga) at Lac des Mille Lacs.

Gabbro dikes transect tonalite of the Marmion batholith as well as the clastic sedimentary and intermediate to felsic volcanic rocks. The gabbro dikes gradually increase in abundance south of Mercutio Lake and coalesce as a "greenstone belt" of approximately 2 km width along the north side of Crooked Pine Lake (*see* Figure 11.2). The gabbro is typically composed of medium- to coarse-grained, dark-green to black massive amphibolite. The gabbroic magma may have progressively evolved from intermediate to mafic and possibly ultramafic composition. The compositional evolution is demonstrated by early dikes of coarse-grained leucogabbro cut by late dikes of fine-grained gabbro and melagabbro. The gabbro dikes are folded and extensively fractured and are locally cut by shear zones within which the amphibole is retrogressed to an assemblage of chlorite+carbonate with associated quartz veins. Rare outcrops of dark green massive to pillowed volcanic rocks are observed within the gabbroic sequences.

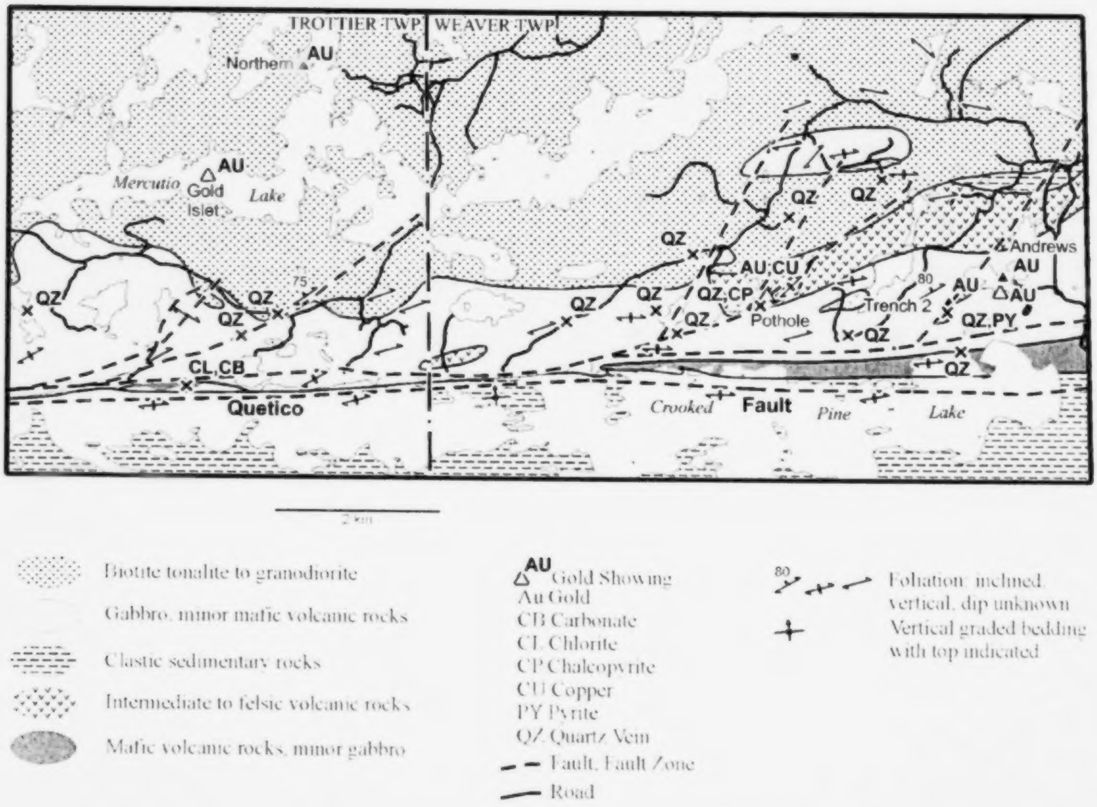

TROTTIER TWP
WEAVER TWP
Northern AU
AU
Mercutio
Gold Islet
Lake
QZ
QZ
AU;CU
QZ
QZ;CP
QZ
Pothole
Trench 2
80
AU
Andrews
AU
AU
QZ,PY
QZ
QZ
75
QZ
QZ
QZ
CL,CB
Quetico
Crooked
Fault
Pine
Lake
2 km
Biotite tonalite to granodiorite
Gabbro, minor mafic volcanic rocks
Clastic sedimentary rocks
Intermediate to felsic volcanic rocks
Mafic volcanic rocks, minor gabbro
AU Gold Showing
Au Gold
CB Carbonate
CL Chlorite
CP Chalcopyrite
CU Copper
PY Pyrite
QZ Quartz Vein
Fault, Fault Zone
Road
80
Foliation: inclined, vertical, dip unknown
Vertical graded bedding with top indicated

Figure 11.2. Geology of the eastern Crooked Pine Lake area.

Thin, discontinuous and locally deformed mafic volcanic units occur at the north shore of Crooked Pine Lake and mark the extreme southern limit of the Marmion terrane. The volcanic rocks are fine grained, pale green and typically pillowed. The volcanic rocks are composed of an assemblage of zoisite+actinolite+plagioclase that are weakly deformed and of chlorite schists where shearing is prevalent. In the field, the volcanic units are distinguished from the gabbroic sequence to the north on the basis of a finer grain size, prevalence of pillows and lower metamorphic grade.

Clastic sedimentary sequences of the Quetico Subprovince occur at the south side of the Crooked Pine Lake area. The sedimentary sequence is composed of thin- to thick-bedded wacke and siltstone. Many sedimentary beds are graded from a sandy base to a laminated silty top and indicate an overall northward younging.

The Quetico fault extends easterly through the Crooked Pine Lake area and is localized at the boundary between mafic rocks of the Marmion terrane and sedimentary rocks of the Quetico Subprovince. The width of the fault varies from tens to hundreds of metres across which supracrustal country rocks are converted to chlorite schists. The schists are locally crenulated and cut by quartz+carbonate veins and alteration zones. The gabbroic rocks tend to resist development of broad zones of schistose fabric, but instead have shearing localized within narrow brittle deformation zones. New mapping has defined several secondary faults of overall northeast to north-northeast trend in the Crooked Pine Lake area (*see* Figure 11.2). The secondary faults splay and curve north from the Quetico fault and extend for several kilometres attaining widths of up to several tens of metres. Country rocks are altered to assemblages of chlorite+carbonate with associated quartz veins in the secondary faults.

Numerous mineral occurrences are identified in the eastern Crooked Pine Lake area. The major occurrences, summarized in Table 11.1 consist of gold with minor silver and copper associated with quartz veins in shear zones. The highest gold values tend to occur where accessory pyrite, chalcopyrite and arsenopyrite are disseminated within the quartz veins. The broadest development of mineralized quartz occurs where shear zones transect lithologically complex areas such as the contacts of mesoscopic tonalite enclaves within gabbro. The mineralized shear zones range in width from a few metres to tens of metres. The present mapping combined with airphoto lineament analysis demonstrates a strong association of gold with the northeast- to north-northeast-trending secondary faults (*see* Figure 11.2). The secondary faults provide a useful guide for gold exploration.

GEOLOGY OF THE WESTERN STEEP ROCK LAKE AREA

The western Steep Rock Lake area is situated 15 km west of Atikokan, Ontario, and occupies the western part of the Steep Rock Lake greenstone belt. Southern parts of the area can be reached by water from Perch Lake on the Seine River system. Northern parts of the area are accessed by the Valerie Falls road, which branches south from Highway 622.

A broad (1 km wide) curved unit of intermediate to felsic volcanic rocks occupies the western extent of the Steep Rock Lake greenstone belt in the area of Modred, Harold and Tea lakes (Figure 11.3). The volcanic rocks are fine grained, white, homogeneous and commonly show quartz and feldspar megacrysts. The volcanic sequence probably represents a series of felsic flows and subvolcanic intrusions. Volcanic tuffs and breccias are noted with the megacrystic rocks northeast of Modred Lake. The intermediate to felsic volcanic sequence is strongly deformed in the area of Tea Lake and the Zephyr showing where sericite+carbonate schists with a closely spaced cleavage are developed. Although undated, the intermediate to felsic volcanic rocks are possibly correlative with volcanic rocks (2.92 Ga) at the north side of the Perch Lake greenstone belt, 15 km west of the present area (Tomlinson et al. 2003).

Table 11.1. Summary of mineral occurrences in the eastern Crooked Pine Lake area (for locations, *see* Figure 11.2).

Name	Previous Work	Gold Association	Significant Assays	Selected References
Pothole	Trenching, sampling soil geochemistry and drilling (1963 to 2003)	Quartz veins with minor sulphide minerals in sheared composite tonalite, gabbro and intermediate volcanic rocks	Up to 11.5 g/t gold with the highest assays associated with arsenopyrite; minor silver and copper	Schnieders and Dutka (1985)[1,2] Assessment File 2.26671 (Band-Ore Resources Ltd; M. Leahey, 2003)[1]
Andrews	Trenching, sampling and drilling by several prospectors and companies (1980s)	Sheared and chlorite +carbonate altered intermediate volcanic rocks	Up to 10.6 g/t gold with the highest values derived from quartz veins with arsenopyrite	Assessment File 2.13124 (Grand Oakes Resources Corp; C. Larouche, 1990)[1,2]
Trenches 2 and 3 (Grand Oakes Resources Corp)	Stripping, sampling and drilling (1980s)	Quartz veins with minor sulphide minerals in sheared intermediate tuff, tonalite and gabbro	Grab samples of up to 7.4 g/t gold from quartz pods	Assessment File 2.13124 (Grand Oakes Resources Corp; C. Larouche, 1990)[1,2]
Partridge (Gold Islet and Northern Occurrences)	Historic prospecting and assays by government geologists; resampling in 1996	Quartz veins developed in sheared tonalite and gabbro	0.006 to 0.015 g/t gold (1996 sampling)	Ontario Prospectors Assistance Program Report 95-313; K. Fenwick, 1996)[1]

[1] Assessment Files and Reports of the Ontario Prospectors Assistance Program are located in the office of the Resident Geologist, Thunder Bay, Ontario for area 52B14SE;

[2] can be accessed through the Ministry of Northern Development and Mines' Earth Resources and Mineral Exploration Site (ERMES) at http://www.mndm.gov.on.ca/mndm/mines/ermes/default_e.asp

Adjacent to the Seine River, mafic volcanic rocks and associated gabbro occupy a broad curved unit south of the intermediate to felsic volcanic rocks (*see* Figure 11.3). Thin units of mafic volcanic rocks also occur within and marginal to the felsic volcanic sequences north of Modred Lake. The mafic rocks are fine to medium grained, dark green and homogeneous and rarely show recognizable pillows and flow-boundaries. The mafic sequence appears to be a combination of mafic flows and gabbro intrusions whose relative proportions are difficult to estimate. The contacts with felsic volcanic rocks are obscure and at least locally sheared. Although amphibole appears to be the predominant mafic mineral, strong deformation has developed extensive zones of chlorite+carbonate schists in western parts of the mafic sequence.

Dikes and irregular masses of gabbro crosscut the intermediate to felsic volcanic unit and the felsic plutonic rocks. The gabbro is variably fine to coarse grained and dark green. Gabbro dikes are locally folded and the majority of dikes show a well-developed cleavage. Chlorite+carbonate schists are developed in the hinges of folded gabbro dikes and in sheared gabbro. The relation of the gabbro dikes to the larger unit of massive mafic volcanic rocks and gabbro is unclear. On the one hand, at least some of the gabbro dikes may represent the same magmatic event as the massive mafic volcanic unit. On the other hand, large cleared outcrops in the area of the Elizabeth Mine show crosscutting mafic dikes, and imply several generations of mafic dike emplacement.

A sequence of pillowed mafic volcanic rocks extends broadly through southern parts of the present area (*see* Figure 11.3) and appears to be distinct from the massive mafic sequence described previously. Although locally massive, the majority of outcrops show large, round thick-rimmed pillows. The mafic volcanic rocks are fine grained and pale green with an assemblage of zoisite+actinolite+plagioclase. Two thin units of serpentinite with talc, probably representing altered komatiite are identified within the mafic sequence. The pillowed mafic sequence is also cut by a series of thin deformed and schistose quartz-porphyritic units that appear to be late tonalitic dikes. The pillowed mafic sequence is distinguished from the massive mafic sequence to the north on the basis of lower metamorphic grade, somewhat lower level of deformation and the widespread presence of pillows. The pillowed mafic sequence is provisionally correlated with the Witch Bay assemblage of Wilks and Nisbet (1988), which occurs extensively at Steep Rock Lake 5 km east of the present area.

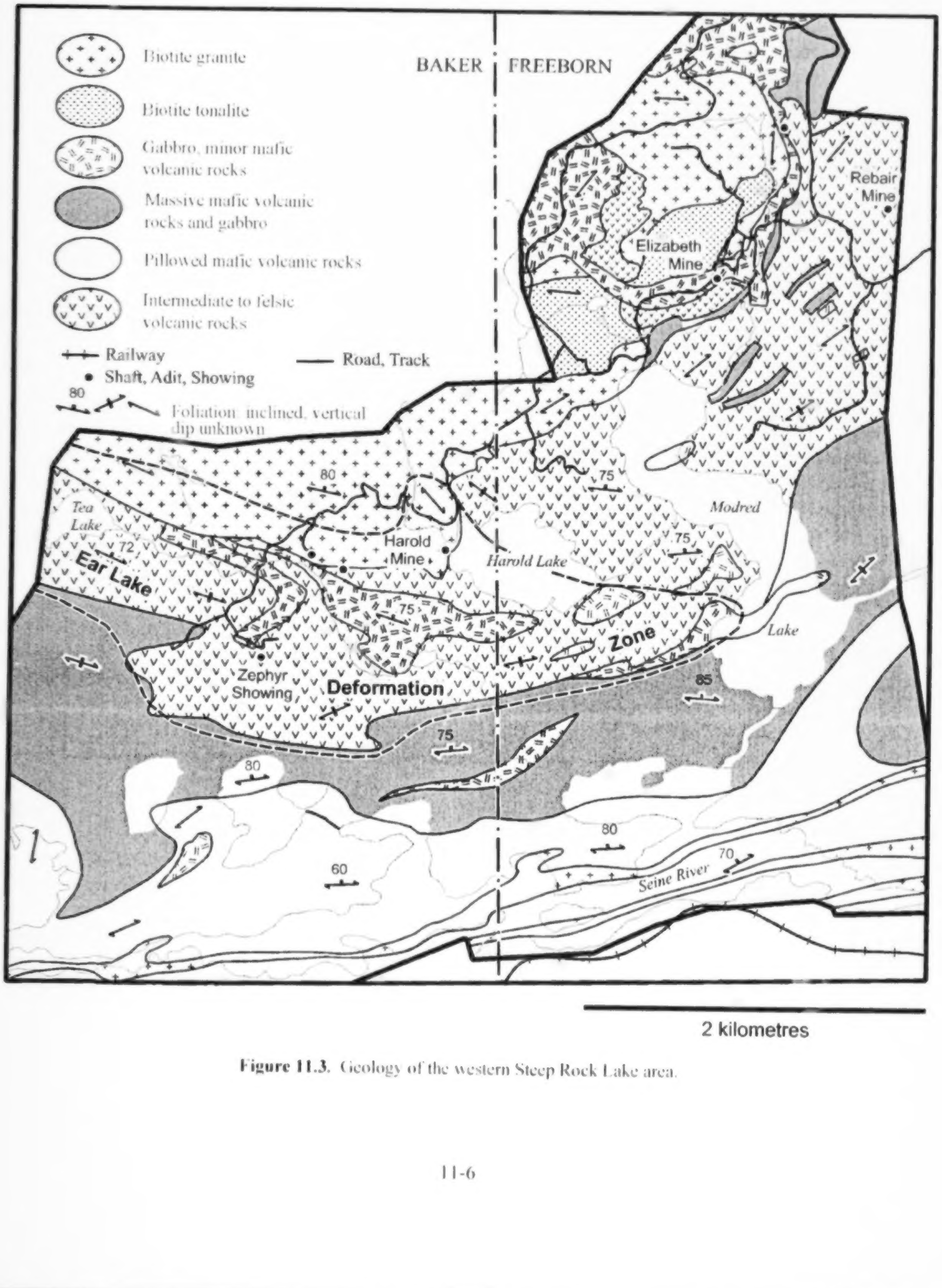

Biotite granite
Biotite tonalite
Gabbro, minor mafic volcanic rocks
Massive mafic volcanic rocks and gabbro
Pillowed mafic volcanic rocks
Intermediate to felsic volcanic rocks
Railway
Road, Track
Shaft, Adit, Showing
Foliation: inclined, vertical, dip unknown
80
BAKER
FREEBORN
Rebair Mine
Elizabeth Mine
Tea Lake
Ear Lake
Harold Mine
Harold Lake
Modred
Lake
Zephyr Showing
Deformation
Zone
Seine River
80
75
72
75
75
85
75
80
80
70
60
2 kilometres

Figure 11.3. Geology of the western Steep Rock Lake area.

thin units of serpentinite with talc, probably representing altered komatiite are identified within the mafic sequence. The pillowed mafic sequence is also cut by a series of thin deformed and schistose quartz-porphyritic units that appear to be late tonalitic dikes. The pillowed mafic sequence is distinguished from the massive mafic sequence to the north on the basis of lower metamorphic grade, somewhat lower level of deformation and the widespread presence of pillows. The pillowed mafic sequence is provisionally correlated with the Witch Bay assemblage of Wilks and Nisbet (1988), which occurs extensively at Steep Rock Lake 5 km east of the present area.

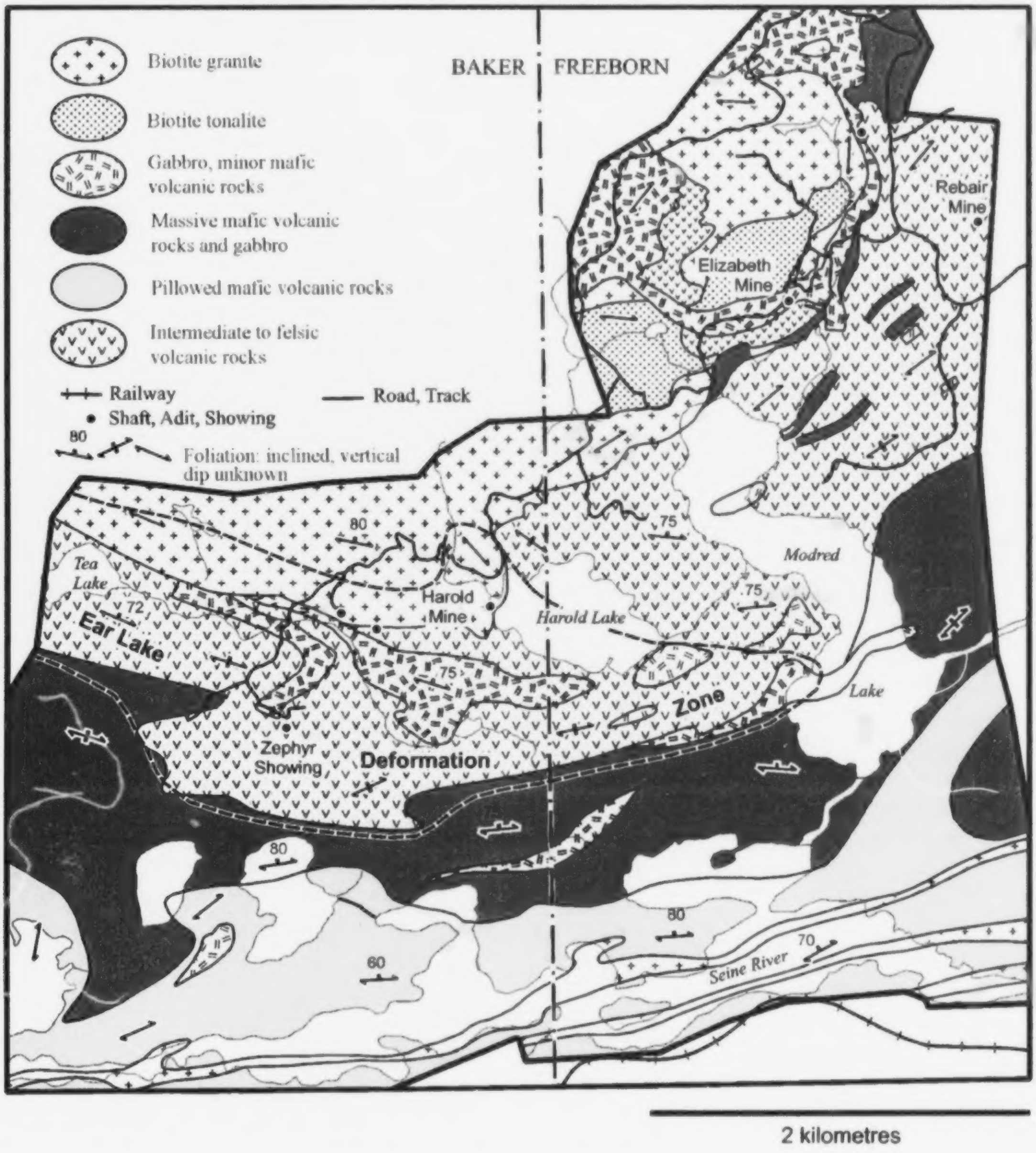

Biotite granite
Biotite tonalite
Gabbro, minor mafic volcanic rocks
Massive mafic volcanic rocks and gabbro
Pillowed mafic volcanic rocks
Intermediate to felsic volcanic rocks
Railway
Road, Track
Shaft, Adit, Showing
80
Foliation: inclined, vertical dip unknown
BAKER
FREEBORN
Rebair Mine
Elizabeth Mine
Tea Lake
72
Ear Lake
80
Harold Mine
Harold Lake
75
Modred
75
Lake
75
Zone
Zephyr Showing
Deformation
75
80
80
60
70
Seine River
2 kilometres

Figure 11.3. Geology of the western Steep Rock Lake area.

Felsic plutonic rocks including biotite tonalite and biotite granite occur northwest of the Steep Rock greenstone belt. The felsic plutonic rocks are typically coarse grained, white to pink and massive to foliated. Biotite tonalite as well as biotite granite intrudes the intermediate to felsic volcanic sequences. West of Harold Lake, the biotite tonalite is strongly foliated and cut by west-northwest-trending shear zones. Lamprophyre dikes cut biotite granite in large cleared outcrops at the Elizabeth Mine. The lamprophyre dikes are typically less than 1 m wide and appear to represent the youngest magmatic rocks in the area.

Deformation is concentrated along the arcuate northwest margin of the Steep Rock Lake greenstone belt. The broad Ear Lake deformation zone (Stone, Kamineni and Jackson 1992) extends west-northwest from Harold Lake and attains a width of 1.5 km within which intermediate to felsic volcanic rocks and adjacent tonalite and mafic rocks are strongly sheared and altered. The alteration has produced a variety of greenschist-facies mineral assemblages in deformed rocks including chlorite+carbonate schists and sericite+carbonate schists with associated quartz. Although somewhat less pervasively deformed, the intermediate to felsic volcanic rocks extending northeast from Harold Lake host numerous mesoscopic shear zones. The small faults trend mainly northeasterly and are preferentially developed at lithologic contacts. Quartz veins and alteration halos characterized by assemblages of greenschist-facies minerals are associated with the shear zones.

Numerous gold occurrences, represented by a variety of trenches, adits, shafts and stripped outcrops are distributed along the western margin of the Steep Rock Lake greenstone belt. Two of these, the Elizabeth and Harold mines, have been known for a century and have produced small amounts of gold (Table 11.2). The Elizabeth, Harold and Zephyr occurrences were explored by Société Minière Mimiska Inc. in the 1980s and subsequently by a variety of other exploration firms with the result that significant resources are delineated. The gold is concentrated primarily with accessory sulphide and telluride minerals in quartz veins. The quartz veins are concentrated within strongly deformed and altered rocks and attain their greatest size where the deformation encompasses lithologically complex areas such as the greenstone belt contact or sequences of volcanic rocks cut by gabbro dikes. The Zephyr and Harold showings are situated within the regionally extensive Ear Lake deformation zone, whereas numerous mineralized veins at the Elizabeth and Rebair showings are associated with smaller, mainly northeast-trending shear zones.

SOIL SAMPLING

Soil sampling was done concurrently with bedrock mapping at the eastern Crooked Pine Lake and western Steep Rock Lake areas. At these localities, bedrock tends to be covered by till to a depth of approximately 1 m with thicker accumulations of till occurring in topographic depressions. Small areas of glaciofluvial outwash deposits and organic deposits occur in both areas and glaciolacustrine silt blankets low-lying southern parts of the Steep Rock Lake area. In general, till could be sampled on somewhat elevated terrain in most parts of both areas. Pits were dug to depths ranging from 0.3 to 1.0 m so as to obtain till at the bedrock surface. At a few sites, glaciofluvial sand and gravel were intersected. However, the majority of samples yielded approximately 1 kg of slightly weathered silty till in direct contact with bedrock.

Soil samples were air-dried and submitted to the Geoscience Laboratories in Sudbury. Analysis of the soil involved initial screening of the material to 250 mesh followed by aqua regia digestion of 30.0 g of the <63 μm fraction and analysis for a range of metals including gold by mass spectrometry.

Table 11.2. Summary of gold occurrences in the western Steep Rock Lake area (for locations, see Figure 11.3).

Name	Previous Work	Gold Association	Production, Resources and Significant Assays	Selected References
Rebair	Trenching, shaft sinking, limited drilling (1930s)	Pyritic quartz + carbonate veins in shear zones cutting felsic volcanic rock	4.1 g/t gold over 0.91 m (1936); 0.082 g/t (1982); trace of gold (1983)	Wilkinson (1982)[1,2]; Schnieders and Dutka (1985)[1,2]
Elizabeth	Mining, drilling stripping, geology, geophysics	Numerous mainly sugary quartz + carbonate veins with accessory sulphide minerals. The veins occur in NE- to N-trending shear zones preferentially developed at lithologic contacts.	13 405 g gold produced (1908–1913) Drill-indicated resources of 250 000 t grading 4.8 g/t gold (1990)	Schnieders and Dutka (1985)[1,2]; Lavigne, Scott and Sarvas (1990)[1,2]
Harold	Mining, drilling, stripping, geology, geophysics	Numerous quartz veins developed in complexly deformed contact zone between biotite tonalite and felsic volcanic rocks	21 365 g gold produced from 1026 t of ore averaging 20.2 g/t (1896); Drill intersections of 6.17 g/t over 0.5 m and 11.31 g/t over 2.9 m (1988)	Wilkinson (1982)[1,2] Assessment File 2.18866 (888726 Ontario Inc, T. Maitland and G. Clark, 1997)[1]
Zephyr	Stripping, drilling (1984–1996)	Quartz+carbonate veins developed in sheared and folded sequence of felsic volcanic rocks cut by gabbro dikes	Drill intersection of 6.14 g/t gold over 10.35 m Drill-indicated resources of 45 000 t grading 7.2 g/t (1990)	Assessment Report Société Minière Mimiska; B. Nelson (1996)[1, 2 (in 52B13SE)]; Lavigne, Scott and Sarvas (1990)[1,2]

[1] Assessment Files and Reports of the Ontario Prospectors Assistance Program are located in the office of the Resident Geologist, Thunder Bay, Ontario for area 52B13SW

[2] can be accessed through the Ministry of Northern Development and Mines' Earth Resources and Mineral Exploration Site (ERMES) at http://www.mndm.gov.on.ca/mndm/mines/ermes/default_e.asp

A total of 87 samples were collected from the eastern Crooked Pine Lake area in the 2005 field season. The samples are distributed regionally over the belt of gabbroic and volcanic rocks as well as the southern part of the Marmion batholith. In the Crooked Pine Lake area and the western Steep Rock Lake area, the predominant direction of glacial ice movement is approximately 215°. An effort was made to sample "down-ice" from known gold occurrences as listed in Table 11.1 as well as the splay faults (*see* Figure 11.2) that are potential hosts for gold mineralization. Results of the 2005 soil sampling are not yet available, however, it is hoped that evaluation of the analytical results can test whether glacially dispersed soil anomalies are associated with bedrock gold occurrences.

A total of 144 soil samples were taken from the southwest part of the western Steep Rock Lake area in 2004 and an additional 90 samples were dug from the northeastern part of this area in the 2005 season. Of these samples, only the preliminary results for the 2004 data are available, as shown in Figure 11.4. The gold contents of the 2004 soil samples ranges up to 65 parts per billion (ppb) with 5 ppb representing an approximate median value. The gold content of soil samples is shown by proportional dots in Figure 11.4 and provides useful guidance for gold exploration. Notably, till samples taken a few metres to tens of meters "down-ice" from known gold occurrences at the Zephyr, Harold and at several stripped outcrops northeast of Harold Lake contain anomalous gold. This provides evidence for a correlation between the gold content of till and the gold content of bedrock distributed a short distance "up-ice" from the sample site. Accordingly, the results of the soil sampling may be useful in defining areas of potentially mineralized bedrock. By inspection, many samples distributed broadly between Harold Lake and northern Modred Lake have greater than 5 ppb gold. This area includes the Harold occurrence and several other stripped outcrops known to contain anomalous gold. Secondly, anomalous gold occurs in soil at the Zephyr showing and possibly in a zone extending west of the Zephyr showing in the area south of Tea Lake. Thirdly, many samples distributed broadly along the north side of the Seine River are anomalous. No major bedrock gold occurrences are known in this area.

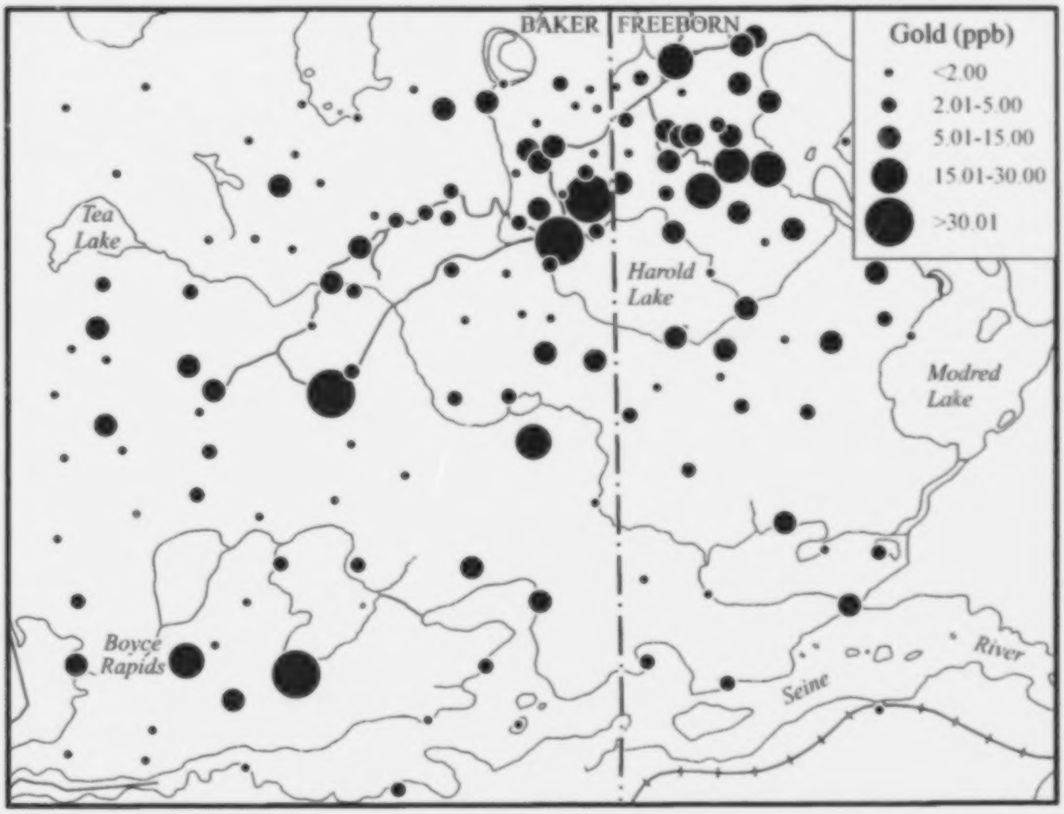


Figure 11.4. Distribution of gold in till, southwestern part of the western Steep Rock Lake area.

SUMMARY

At the majority of gold occurrences in the Crooked Pine Lake and western Steep Rock Lake areas, gold is concentrated with accessory sulphide minerals in quartz+carbonate veins. The veins normally occur within highly deformed rock and appear to attain their greatest size and abundance in areas where the deformation encompasses a variety of different rocks such as tonalite–greenstone contacts, tonalite inclusions within gabbro and volcanic rocks crosscut by gabbro dikes. The deformation appears to have occurred mainly by shearing and has resulted in development of schists in volcanic rocks and a combination of mylonites and cataclastites in more brittle gabbro and tonalite. Alteration zones normally mantle and pervade the mineralized deformation zones and contain greenschist-facies mineral assemblages such as chlorite+carbonate+albite+quartz and sericite+carbonate+albite+quartz. Although mineralized quartz veins are recrystallized and folded at the Elizabeth and Zephyr occurrences indicating that they are mildly deformed, the majority of quartz veins at all localities crosscut tectonites and appear to have been emplaced at a late stage of regional deformation.

At Crooked Pine Lake, the mineralized shear zones trend mainly northeasterly and appear to represent secondary splay faults emanating from the Quetico fault. West of Steep Rock Lake, northeasterly trending mineralized shear zones are also common, although the Zephyr and Harold occurrences are situated within the wide northwesterly trending Ear Lake deformation zone. Broadly, the gold appears to have been deposited from fluids that moved through brittle cavities created by secondary deformation zones associated with the late stages of motion on major faults such as the Quetico and Ear Lake faults.

The majority of gold showings were discovered by prospecting. The success of prospecting is remarkable in view of the fact that approximately 90% of the bedrock is covered by soil, lakes and organic deposits. It is probable that other unexposed and undiscovered mineralization occurs in these areas. Till sampling surveys may be useful for detection of buried mineralization. Preliminary results of the present work show anomalous gold within till that has been glacially dispersed "down-ice" from mineralized zones. Hence, closely spaced till sampling surveys may help to detect unexposed gold mineralization.

A major challenge to gold exploration programs has been the ability to define sufficient volumes of ore to be economically mined. Although many veins yield good assays and visible gold, the veins are too small or widely spaced to permit a viable mining operation. In this context, a change in exploration philosophy may be warranted. Rather than searching for individual high-grade veins, exploration might be more successful if focussed on larger targets possibly containing multiple veins or broader areas of low-grade mineralization. The secondary faults at Crooked Pine Lake are potential exploration targets. Many known gold occurrences are distributed along these structures and possibly by systematically exploring the kilometre-scale structures, mineable ore bodies can be defined. Till sampling surveys may also be useful for definition of large mineralized areas. For example, many till samples in the area between northern Harold and Modred lakes contain anomalous gold. These may be an indication of broadly dispersed gold mineralization in the bedrock.

REFERENCES

Lavigne, M.J. and Scott, J.F. 1995. Gold deposits of the Marmion Lake Batholith; *in* Summary of Field Work and Other Activities 1995, Ontario Geological Survey, Miscellaneous Paper 164, p. 147-149.

Lavigne, M.J., Scott, J.F. and Sarvas, P. 1990. Thunder Bay Resident Geologist's District—1990; *in* Report of Activities 1990, Resident Geologists, Ontario Geological Survey, Miscellaneous Paper 152, p. 107-126.

Percival, J.A. and Williams, H.R. 1989. Late Archean Quetico accretionary complex, Superior Province, Canada; Geology, v.17, p.23-25.

Schnieders, B.R. and Dutka, R.J. 1985. Property visits and reports of the Atikokan economic geologist, 1979–1983, Atikokan geological survey; Ontario Geological Survey, Open File Report 5539, 512p.

Stone, D. 2004. Geology of the Lac des Mille Lacs area; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.12-1 to 12-11.

Stone, D., Kamineni, D.C. and Jackson, M.C. 1992. Geology of the Atikokan area; Geological Survey of Canada, Bulletin 405, 106p.

Stone, D., Pufahl, P. and Carter, J. 1995a. Precambrian geology, Atikokan area; Ontario Geological Survey, Preliminary Map P.3349, scale 1:50 000.

——— 1995b. Precambrian geology, Sapawe area; Ontario Geological Survey, Preliminary Map P.3350, scale 1:50 000.

Tomlinson, K.Y., Davis, D.W., Stone, D. and Hart, T.H. 2003. U-Pb age and Nd isotopic evidence for Archean terrane development and crustal recycling in the south-central Wabigoon subprovince, Canada; Contributions to Mineralogy and Petrology, v.144, p.684-702.

Tomlinson, K.Y., Stott, G.M., Percival, J.A. and Stone, D. 2004. Basement terrane correlations and crustal recycling in the western Superior Province: Nd isotopic character of granitoid and felsic volcanic rocks in the Wabigoon Subprovince, N. Ontario, Canada, Precambrian Research, v.132, p.245-274.

Wilkinson, S.J. 1982. Gold deposits of the Atikokan area; Ontario Geological Survey, Mineral Deposits Circular 24, 54p.

Wilks, M.E. and Nisbet, E.G. 1988. Stratigraphy of the Steep Rock Group, northwest Ontario: a major Archaean unconformity and Archaean stromatolites; Canadian Journal of Earth Sciences, v.25, p.370-391.

12. Project Unit 05-002. Lake Nipigon Synthesis

T.R. Hart[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario

INTRODUCTION

This project is a single-year compilation of the various data sets collected during the Lake Nipigon Region Geoscience Initiative (LNRGI), complemented with a number of adjacent data sets, including the Ontario Treasure Hunt Garden–Obonga airborne geophysical survey and Preliminary Map P.3532 for the Lac des Iles area. The goal of the project is to provide a comprehensive synthesis of the geological data centred on Lake Nipigon to provide an improved regional geological and tectonic framework for the Lake Nipigon area. Products will include hard-copy geological maps, a seamless digital geological compilation, and a synoptic style Open File Report focussing on the Proterozoic rocks and mineral potential of the western Lake Nipigon area.

PROJECT DESCRIPTION

Bedrock mapping of the western Nipigon Embayment was completed over a two-year period at 1:50 000 scale (Figure 12.1) (Hart and Magyarosi 2004; Hart 2005; MacDonald 2004; MacDonald and Tremblay 2005). Mapping of the northern and central areas was conducted under a contract agreement between the Ontario Geological Survey (OGS) and the Ontario Prospectors Association for the LNRGI, whereas the two southern map areas were mapped by the OGS as part of its commitment of in-kind support to the LNRGI. The bedrock mapping projects included preliminary interpretations of the igneous petrogenesis, stratigraphic analysis, and the development of geological cross-sections. These interpretations were completed in co-operation with teams of researchers at Lakehead University, and incorporated newly acquired geophysical data (e.g., OGS 2004a, 2004b), exploration data contributed to the LNRGI by participating companies, and data acquired by re-logging of diamond-drill core. However, complete integration all of the data sets generated by the LNRGI was not possible, as some projects were not completed until after the end of the 2003, and, in some cases, the 2004 mapping projects.

This project is a single-year compilation of the various bedrock mapping data sets as well as those generated from the other detailed studies that were conducted as part of the LNRGI. These include geochronology (e.g., Heaman et al. 2005; Heaman and Easton 2005), lithostratigraphic analysis (e.g., Fralick, Metsaranta and Rogala 2005), igneous petrogenetic studies of the diabase sills (e.g., Richardson and Hollings 2005), and a detailed study of the mineralization in the Seagull intrusion (e.g., Heggie 2005). Collaboration with these aforementioned researchers will continue with the integration of the results of these studies with the geological interpretation completed during this project. The compilation will concentrate on the Proterozoic rocks of the western Lake Nipigon area, but will also include adjacent Archean rocks which appear to correlate across, and form the basement rocks to, the Nipigon Embayment.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.12-1 to 12-6.

© Queen's Printer for Ontario, 2005

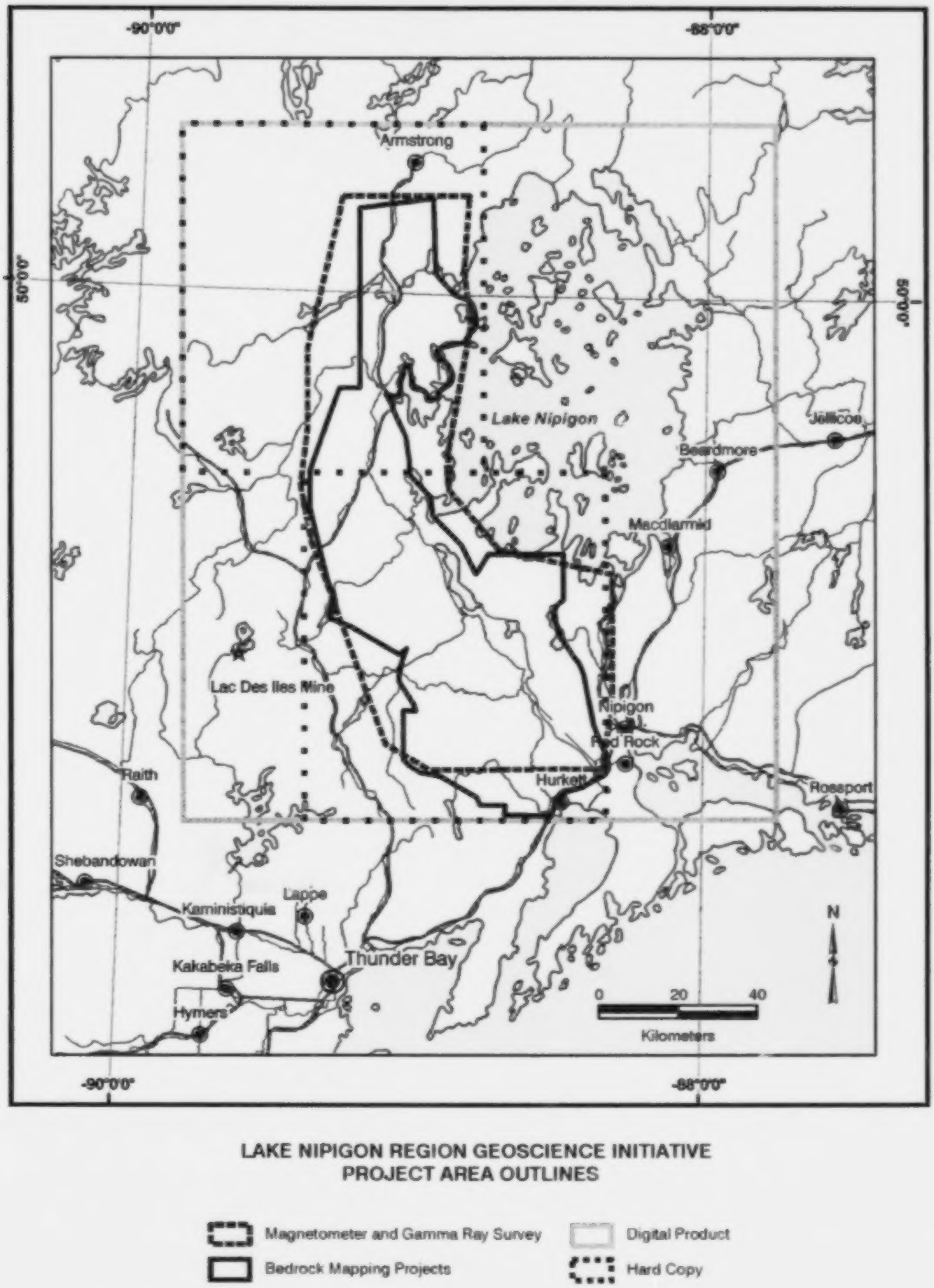

-90°0'0"
-88°0'0"
50°0'0"
50°0'0"
Armstrong
Lake Nipigon
Jellicoe
Beardmore
Macdiarmid
Lac Des Iles Mine
Nipigon
Red Rock
Hurkett
Rossport
Raith
Shebandowan
Kaministiquia
Lappe
Thunder Bay
Kakabeka Falls
Hymers
N
0
20
40
Kilometers
-90°0'0"
-88°0'0"
LAKE NIPIGON REGION GEOSCIENCE INITIATIVE
PROJECT AREA OUTLINES
Magnetometer and Gamma Ray Survey
Bedrock Mapping Projects
Digital Product
Hard Copy

Figure 12.1. An outline of the area of the Lake Nipigon Synthesis digital compilation, with outlines of the 1:100 000 scale hard-copy maps, the area of the LNRGI bedrock mapping projects, and the airborne geophysical survey area.

PRODUCTS

Products generated during this project will include hard-copy geological maps, a seamless digital geological compilation, and a synoptic style Open File Report focussing on the Proterozoic rocks and mineral potential of the western Lake Nipigon area. Two hard-copy maps at 1:100 000 scale will cover the western part of the Nipigon Embayment, including the area of the 2003 and 2004 mapping projects (*see* Figure 12.1). These maps will complement the area covered by the LNRGI 1:100 000 scale geophysical map sheets for the airborne magnetic and radiometric survey and the ground gravity survey. A seamless digital 1:100 000 scale geological compilation will include the area of the hard-copy maps, and an area equivalent to 2 additional 1:100 000 scale maps covering the eastern portion of the Lake Nipigon area (*see* Figure 12.1). The digital compilation will be GIS based and contain additional data incorporated into the geological interpretation, including diamond-drill hole, lithogeochemical, geochronological databases, and geophysical images. The Open File Report will contain a description of the lithologies, structures, and economic geology of the western Lake Nipigon area based on the geological reports generated during the LNRGI, with additional examination of analytical data including the lithogeochemistry and geophysical surveys. This report will be multi-authored, and also contain contributions by other OGS personnel involved with LNRGI, including geophysical surveys and results of geophysical modelling by D.R.B. Rainsford.

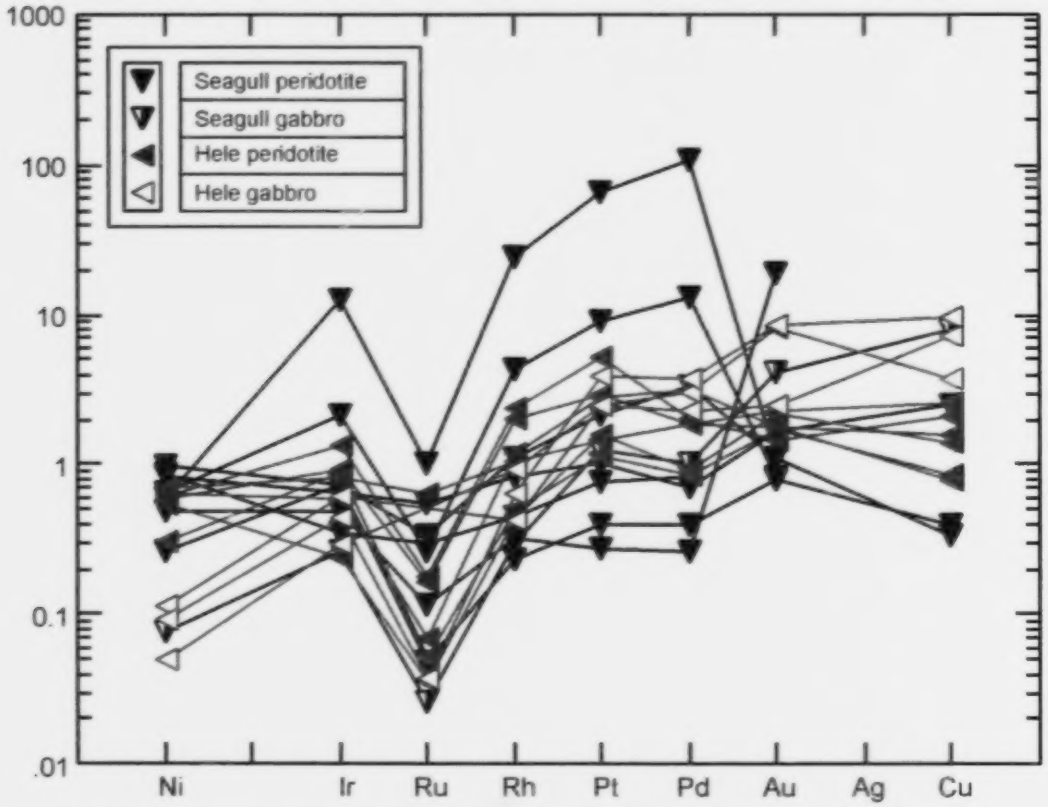


Figure 12.2. Most of the ultramafic intrusions have relatively flat positive slopes on mantle normalized PGE diagrams (e.g., Hele intrusion), with convex patterns typical of most PGE deposits displayed by mineralized samples from the Seagull intrusion (e.g., Barnes et al. 1993).

DISCUSSION

One of the main aims of this project is to continue the work started by the LNRGI leading toward an improved geological and tectonic framework for the Lake Nipigon area. This improved framework may also provide additional recommendations for mineral exploration in the area. A large volume of information was generated during the mapping projects, but there was limited time available for detailed examination and interpretation of these large data sets, most notably, lithogeochemistry and structure.

The lithogeochemistry of the ultramafic intrusions was recently re-examined (Hart et al. 2005), with an emphasis on the platinum group elements (PGE). Most of the ultramafic intrusions have relatively flat positive slopes on mantle-normalized PGE diagrams in distinct contrast with the concave shape observed for samples of the Nipigon diabase sills (Figure 12.2). The peridotites from the different intrusions have elevated Cu/Pd ratios and depleted Pd values that mirror the depleted Cu/Pd ratios and elevated Pd values of the PGE mineralized portions of the Seagull intrusion (Figure 12.3) (data from Hart 2005; East West Resource Corporation 2004a, 2004b). The presence of elevated ratios in some of the other intrusions suggests that they may also be part of mineralized magmatic systems, but more detailed sampling is required to determine if mineralization was preserved or present in the intrusions.

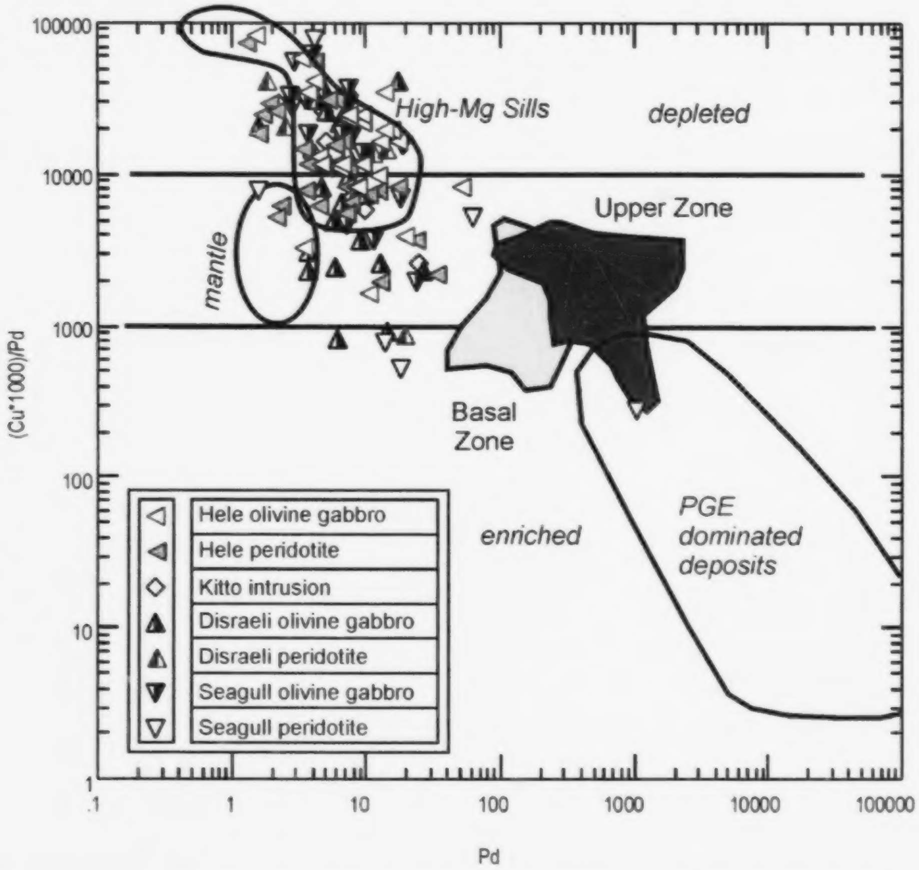


Figure 12.3. Elevated Cu/Pd ratios and Pd depletion for the peridotites from most of the ultramafic intrusions, and the high-Mg sills, mirrors the depleted Cu/Pd ratios and elevated Pd values associated with the PGE mineralization in the Seagull intrusion (data *from* Hart 2005; East West Resource Corporation 2004a, 2004b), suggesting they may also be part of mineralized magmatic systems (*after* Barnes et al. 1993).

The lithogeochemistry of the high-Mg sills scattered through the Nipigon Embayment was also re-examined (MacDonald and Tremblay 2005; Richardson and Hollings 2005; Hart and Magyarosi 2004; Hart 2005). These high-Mg sills generally have moderate Gd/Yb ratios comparable to those of the Kitto intrusion, except for the Shillabeer sill that has ratios that more closely resemble the Disraeli, Seagull and Hele intrusions (e.g., Hart 2005; MacDonald and Tremblay 2005). The sills may be either separate bodies or the peripheral portions of larger intrusions. Some samples from the high-Mg sills have elevated Cu/Pd ratios that overlap with the ratios observed in the mafic to ultramafic intrusions (*see* Figure 12.3), and Cu/Zr ratios of <0.6, which may be a result of either sulphide segregation or crustal contamination (e.g., Maier, Barnes and Marsh 2003). These ratios suggest that the sills may also be part of mineralized magmatic systems, and an indication of additional mineralization in the Nipigon Embayment. The structural interpretation completed during the mapping projects suggested that the Black Sturgeon fault zone may be the product of two major regional fault systems, one trending north and the other trending northwest (MacDonald and Tremblay 2005; Hart 2005). The location and form of the Seagull, Disraeli and Hele intrusions suggests that their emplacement may have been controlled by a combination of these two fault systems. The northwest-trending structures appear to be re-activated Archean structures, and can be traced for 50 km into the adjacent central Wabigoon Subprovince (e.g., Hart 2005). Inclusion of the areas of Archean rocks peripheral to the Nipigon Embayment will allow this project to more fully examine the relationship between the structures in the Archean basement rocks and their control on the Proterozoic geology.

REFERENCES

Barnes, S.J., Couture, J.-F., Sawyer, E.W. and Bouchaib, C. 1993. Nickel-copper occurrences in the Belleterre–Angliers Belt of the Pontiac Subprovince and the use of Cu-Pd ratios in interpreting platinum group element distributions; Economic Geology, v.88, p.1402-1418.

East West Resource Corporation 2004a. PGE horizon extended to additional holes – Seagull intrusion; East West Resources Corporation, News Release, dated July 5, 2004, http://www.eastwestres.com/main.asp?section=news&page=20040705 [accessed September 29, 2005]

———— 2004b. Highly elevated platinum group elements discovered in new horizons at Seagull intrusion; East West Resources Corporation, News Release, dated July 29, 2004; http://www.eastwestres.com/main.asp?section=news&page=20040729 [accessed September 29, 2005]

Fralick, P., Metsaranta, R. and Rogala, B. 2005. Stratigraphy of the Mesoproterozoic Sibley Group and Nipigon Sills; Institute of Lake Superior Geology, 51st Annual Meeting, Nipigon, Ontario, Part 1 – Proceeding and Abstracts, v.51, part 1, 17-18.

Hart, T.R. 2005. Precambrian geology of the southern Black Sturgeon River and Seagull Lake area, Nipigon Embayment, northwestern Ontario; Ontario Geological Survey, Open File Report 6165, 63p.

Hart, T.R. and Magyarosi, Z. 2004. Precambrian geology of the northern Black Sturgeon River and Disraeli Lake area, northwestern Ontario; Ontario Geological Survey, Open File Report 6138, 56p.

Hart, T.R., Hollings, P., Heggie, G. and MacDonald, C.A. 2005. Proterozoic platinum group element mineralization of the Nipigon Embayment, northwest Ontario; *in* Extended Abstracts, 10th International Platinum Symposium, August 8–11, 2005, Oulu, Finland, p.362-364.

Heaman, L.M. and Easton, R.M. 2005. Proterozoic history of the Lake Nipigon area, Ontario: constraints from U-Pb zircon and baddeleyite dating; Institute of Lake Superior Geology, 51st Annual Meeting, Nipigon, Ontario, Part 1 – Proceeding and Abstracts, v.51, pt.1, 24-25.

Heaman, L.M., Easton, R.M., Hart, T.R., MacDonald, C.A., Fralick, P. and Hollings, P. 2005. Proterozoic history of the Lake Nipigon area, Ontario: constraints from U-Pb zircon and baddeleyite dating; Canadian Institute of Mining and Metallurgy, Annual Meeting, Toronto 2005, Program with Abstracts, http://www.cim.org/meetings/Admin/reports/TechProg_abstract.cfm?PaperNum=1906&Background=F6EFC9&SessionNum=674 [accessed September 29, 2005].

Heggie, G.J. 2005. Whole rock geochemistry, mineral chemistry, petrology and Pt, Pd mineralization of the Seagull intrusion, northwestern Ontario; unpublished PhD thesis, Lakehead University, Thunder Bay, Ontario, 156p.

MacDonald, C.A. 2004. Precambrian geology of the south Armstrong–Gull Bay area, Nipigon Embayment, northwestern Ontario; Ontario Geological Survey, Open File Report 6136, 42p.

MacDonald, C.A. and Tremblay, E. 2005. Precambrian geology of the west-central map area, Nipigon Embayment, northwestern Ontario; Ontario Geological Survey, Open File Report 6164, 49p.

Maier, W.D., Barnes, S.J. and Marsh, J.S. 2003. The concentration of the noble metals in Southern Africa flood-type basalts and MORB: implications for petrogenesis and magmatic sulphide exploration; Contributions to Mineralogy and Petrology, v.146, p.44-61.

Ontario Geological Survey 2004a. Ontario airborne geophysical surveys, magnetic and gamma-ray spectrometer data, grid and vector data and profile data, Lake Nipigon Embayment area; Ontario Geological Survey, Geophysical Data Set 1047.

——— 2004b. Ontario geophysical surveys, gravity data, grid and point data and vector data, Lake Nipigon Embayment survey; Ontario Geological Survey, Geophysical Data Set 1052.

Richardson, A. and Hollings, P. 2005. Rare earth and isotopic geochemistry of the Keweenawan Nipigon Sills; Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists–Canadian Society of Soil Science, Joint Annual Meeting, Halifax 2005, Abstracts, v.30, p.166-167.

13. Project Unit 04-016. Geology and Mineral Potential of Porter and Vernon Townships, Southern Province

R.M. Easton[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Porter–Vernon map area lies 60 km west-southwest of Sudbury, northeast of Agnew Lake, and is underlain by Paleoproterozoic metasedimentary and metavolcanic rocks of the Huronian Supergroup (Southern Province) and Neoarchean granitic rocks (Superior Province). The area is of interest for several reasons.

1. The area includes mafic intrusive rocks of both the East Bull Lake and the Nipissing intrusive suites, which are the subject of ongoing exploration for Cu-Ni-PGE (platinum group elements) mineralization (e.g., the Shakespeare Ni-Cu deposit: Sutcliffe 2003).
2. The area includes skarn mineralization related to contact metamorphism of calcareous rocks of the Espanola Formation by Nipissing gabbro intrusions.
3. The area includes a variety of breccia units, of unknown age and affinity, many of which are localized along faults.
4. Huronian Supergroup rocks in northern Porter and southern Vernon townships have been interpreted to have been deposited in a graben (e.g., Rousell and Long 1998 and references therein). The western margin of the graben lies on the trend of the same fault system that localized the Paleoproterozoic Spanish River carbonatite complex. Other workers (e.g., Mungall and Hanley 2004 and references therein) have suggested that the distribution of the Huronian Supergroup in the area is related to tectonic activity that occurred after the Sudbury impact event. Each interpretation has different implications with respect to mineral potential.
5. Previous geological mapping in the area largely predates establishment of the current Huronian Supergroup stratigraphic framework, hindering interpretation of the existing maps. In addition, access to the area has also improved considerably in recent years.

PREVIOUS WORK

Porter and Vernon townships were mapped as part of the regional mapping of Collins (1938), who first interpreted a graben in the area. Detailed mapping took place in Porter Township in 1956 and 1957 (Ginn 1961) and in southern Vernon Township in 1969 and 1970 (Ward 1972), at 1:12 000 and 1:15 840 scale, respectively. Marmont (1986) mapped the north half of Vernon Township at 1:15 840 scale. Ginn (1960) and Fairbairn, Hurley and Pinson (1960) reported several K/Ar ages from Porter Township, mostly from Archean granitic rocks. Many of these K/Ar ages were ~1260 Ma, most likely because they were collected near Sudbury diabase dikes in the area, which have a U/Pb age of 1238 Ma (Krogh et al. 1987). Two weeks of reconnaissance mapping was conducted in the study area in 2004 (Easton 2004).

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.13-1 to 13-20.

© Queen's Printer for Ontario, 2005

RESULTS

Geological Overview

The Porter–Vernon map area can be divided into 4 geological domains, as illustrated in Figure 13.1. From south to north these domains are

1. Domain 1. An area south of the Hunter Lake fault that contains metavolcanic and metasedimentary rocks of the Elliot Lake Group and the lower Hough Lake Group, metamorphosed at upper greenschist to amphibolite facies, dominated by east-northeast trends.
2. Domain 2. A faulted domain between the Hunter Lake and South Cygnet faults containing metasedimentary rocks of the Hough Lake and Quirke Lake groups, metamorphosed at lower greenschist facies. These rocks were folded twice (e.g., Porter syncline) prior to being cut by a series of subparallel, northeast-trending faults. Sudbury Breccia is abundant adjacent to and along the major faults.
3. Domain 3. An east-trending domain containing Neoarchean plutonic rocks, metasedimentary rocks of the Hough Lake and Quirke Lake groups and abundant intrusions of Nipissing gabbro. Metamorphism of the Huronian Supergroup is generally at lower greenschist facies, except where contact metamorphosed by Nipissing gabbro intrusions. Broad, east-northeast-trending refolded folds affect all rocks. This domain contains most of the skarn mineralization in the map area. The only known rocks of the East Bull Lake intrusive suite are also found in this domain.
4. Domain 4. This domain underlies the northern one-third of Porter and all of Vernon Township, and contains a north-trending syncline (Vernon syncline, also termed Shiner syncline) of Huronian Supergroup metasedimentary rocks of the Hough Lake, Quirke Lake and Cobalt groups. An outlier of Quirke Lake Group rocks occurs 400 m northeast of the termination of the syncline. Neoarchean granitic rocks bound the Huronian Supergroup strata to the east, west and north. In the north half of this domain, isolated bodies of Nipissing gabbro occur within the area underlain by Neoarchean granitic rocks.

Northwest-trending Sudbury diabase dikes in domains 3 and 4 appear to be continuous for 1 to 3 km along strike, confirming that domains 3 and 4 are less affected by northeast-trending faulting than domains 1 and 2. Results of the mapping program are discussed under the following 5 main headings:

1. observations related to "the Archean basement"
2. observations related to "stratigraphy"
3. observations related to "Nipissing gabbro"
4. observations related to "geophysical properties"
5. observations directly related to "mineralization"

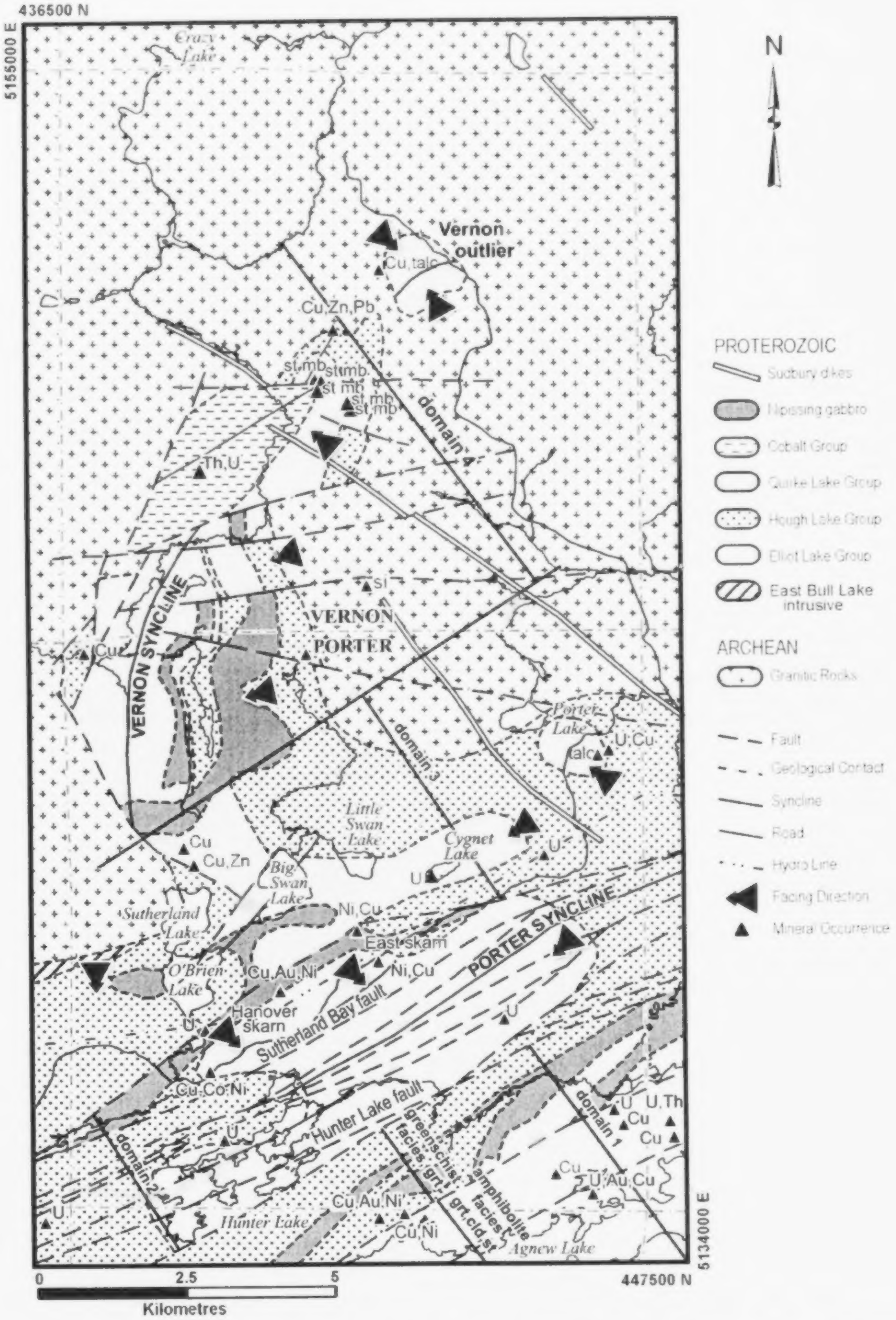

436500 N
5155000 E
Crazy Lake
N
Vernon outlier
Cu,talc
Cu,Zn,Pb
st,mb
st mb
st,mb
domain 4
Th,U
si
VERNON
PORTER
VERNON SYNCLINE
Cu
Porter Lake
U,Cu
talc
domain 3
Little Swan Lake
Cygnet Lake
U
Cu
Cu,Zn
Big Swan Lake
Sutherland Lake
Ni,Cu
East skarn
PORTER SYNCLINE
O'Brien Lake
Cu,Au,Ni
Ni,Cu
Hanover skarn
Sutherland Bay fault
U
Cu,Co,Ni
Hunter Lake fault
greenschist facies, grt
amphibolite facies, grt,cld,st
domain 1
U
U,Th
Cu
Cu
domain 2
Cu
U,Au,Cu
Cu,Au,Ni
Cu,Ni
Hunter Lake
Agnew Lake
5134000 E
0
2.5
5
Kilometres
447500 N
PROTEROZOIC
Sudbury dikes
Nipissing gabbro
Cobalt Group
Quirke Lake Group
Hough Lake Group
Elliot Lake Group
East Bull Lake intrusive
ARCHEAN
Granitic Rocks
Fault
Geological Contact
Syncline
Road
Hydro Line
Facing Direction
Mineral Occurrence

Figure 13.1. Simplified geological map of Porter and Vernon townships, indicating the 4 geological domains described in the text, as well as showing known mineral occurrences present in the map area. Arrows indicate generalized stratigraphic facing directions. Abbreviations: Au = gold, cld = chloritoid, Co = cobalt, Cu = copper, grt = garnet, Ni = nickel, Pb = lead, si = silica, st = staurolite, st mb = stone marble, Th = thorium, U = uranium, Zn = zinc. *Adapted from* Ginn (1961) and Card (1978).

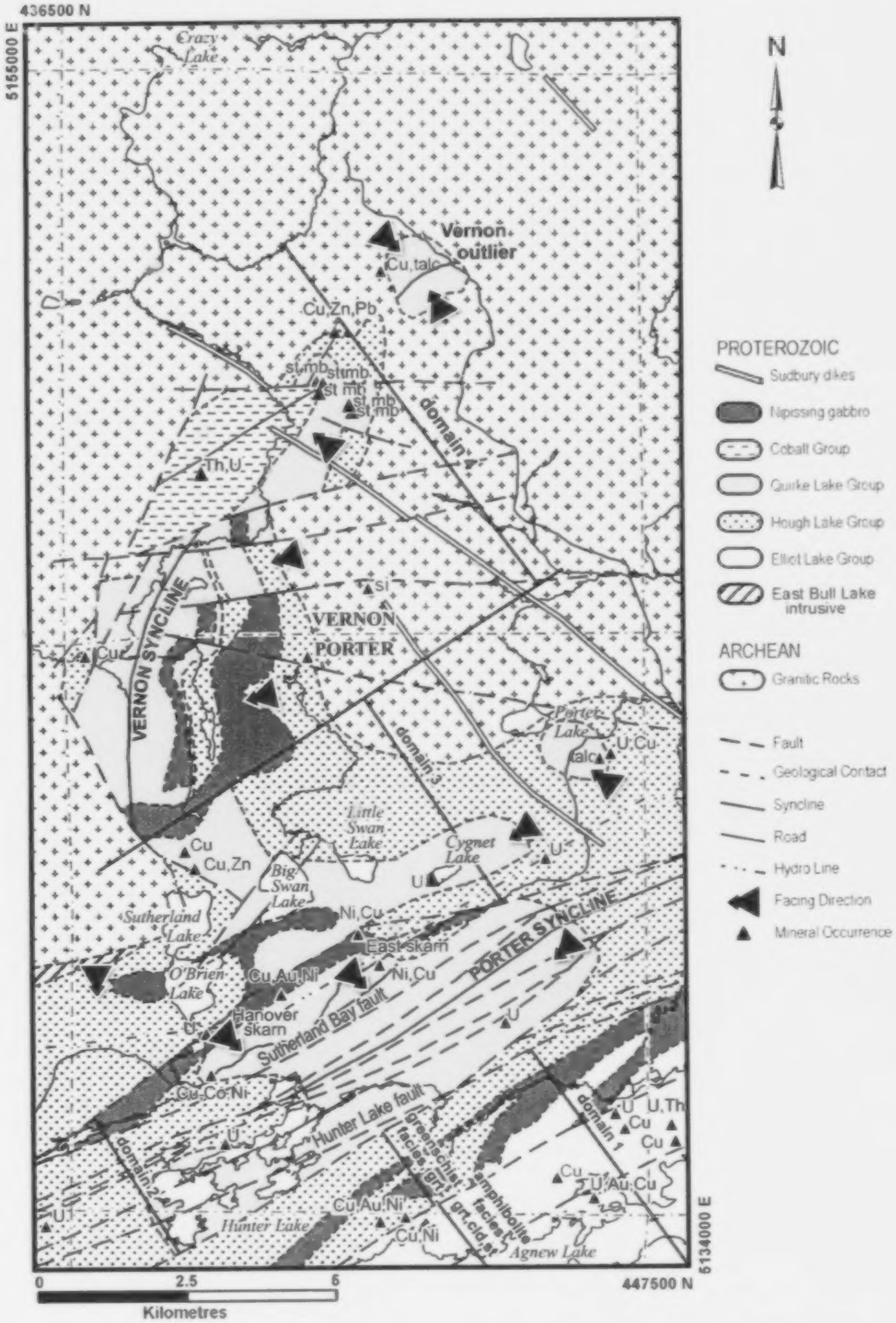

436500 N
5155000 E
N
Crazy Lake
Vernon outlier
Cu,talc
Cu,Zn,Pb
st mb
st mb
st mb
st mb
st mb
domain
Th,U
si
VERNON
PORTER
VERNON SYNCLINE
Cu
domain 3
Porter Lake
talc
U,Cu
Little Swan Lake
Cygnet Lake
U
U
Cu
Cu,Zn
Big Swan Lake
Sutherland Lake
Ni,Cu
East skarn
PORTER SYNCLINE
O'Brien Lake
Cu,Au,Ni
Ni,Cu
Hanover skarn
U
Sutherland Bay fault
U
Cu,Co,Ni
Hunter Lake fault
greenschist facies (grt)
amphibolite facies grt,cld,st
domain 1
U
U,Th
Cu
Cu
Cu
U,Au,Cu
domain 2
U
U
Cu,Au,Ni
Cu,Ni
Hunter Lake
Agnew Lake
5134000 E
447500 N
0
2.5
5
Kilometres
PROTEROZOIC
Sudbury dikes
Nipissing gabbro
Cobalt Group
Quirke Lake Group
Hough Lake Group
Elliot Lake Group
East Bull Lake intrusive
ARCHEAN
Granitic Rocks
Fault
Geological Contact
Syncline
Road
Hydro Line
Facing Direction
Mineral Occurrence

Figure 13.1. Simplified geological map of Porter and Vernon townships, indicating the 4 geological domains described in the text, as well as showing known mineral occurrences present in the map area. Arrows indicate generalized stratigraphic facing directions. Abbreviations: Au = gold, cld = chloritoid, Co = cobalt, Cu = copper, grt = garnet, Ni = nickel, Pb = lead, si = silica, st = staurolite, st mb = stone marble, Th = thorium, U = uranium, Zn = zinc. *Adapted from* Ginn (1961) and Card (1978).

The Archean Basement

Basement rocks to the Huronian Supergroup in the map area consistent almost wholly of a medium- to coarse-grained, pink weathering granite, named the Birch Lake granite by Ginn (1960, 1961). The Birch Lake granite has been intruded by a variety of mafic rocks; including plagioclase-porphyritic mafic dikes related to both the Matachewan diabase dike swarm and the East Bull Lake intrusive suite, large masses of Nipissing gabbro, and olivine diabase dikes of the Sudbury diabase dike swarm. Also present are brown-grey weathering, dark, metamorphosed mafic dikes of unknown age. These mafic dikes are generally west trending. Despite their dark colour, these dikes are andesitic in composition, and are characterized by relatively low Al_2O_3 contents (<13 weight %), elevated K (>18 000 ppm), Rb (>150 ppm), Li (>25 ppm) and Cs (10 ppm) contents. Dikes of this chemical composition have not been previously reported from the Southern Province. The age of these dikes is unknown, other than that they cut Matachewan dikes (~2473 Ma), and that one of these dikes is found within a shear zone cutting rocks of the Mississagi Formation. If this shear zone developed at ~1850 Ma, in relation to either the Penokean orogeny or the Sudbury Event, then these dikes were emplaced sometime between 2473 and 1850 Ma.

There is no noticeable difference in the Birch Lake granite on either side of the Vernon syncline. Furthermore, large masses of Nipissing gabbro occur on both sides of the syncline, and there is no difference in mafic dike abundance or type across the syncline. The similarity in the basement on either side of the syncline would seem to be at odds with the suggestion by Mungall and Hanley (2004) that there have been several kilometres of throw across the fault that locally marks the western margin of the Vernon syncline.

Mafic dikes are most abundant in a west-trending belt, about 500 to 750 m wide, in northern Porter Township, near the contact with the Huronian Supergroup. There is no association between mafic dike abundance and the Huronian Supergroup on either side of the north-trending Vernon syncline. Consequently, the increase in dike abundance near the Huronian Supergroup contact in Porter Township is difficult to interpret. Do the dikes represent feeders to an original overlying, now eroded, volcanic unit?; or, alternatively, were the dikes formed during rifting of the southern Archean cratonic margin, with the Huronian Supergroup rocks subsequently thrust northward back onto to the rifted margin?

Stratigraphy

THE ARCHEAN–PROTEROZOIC CONTACT

Nature of the Basal Huronian Supergroup

Critical to understanding the structural and depositional history of the study area is determining the character of the basal Huronian Supergroup. That is, is the full stratigraphic succession from the Elliot Lake Group to the Cobalt Group present, or was only part of the Huronian Supergroup succession deposited? Apart from domain 1, which contains Elliot Lake Group metavolcanic and metasedimentary rocks, there is little or no indication that rocks stratigraphically below the Pecors Formation (Hough Lake Group) were deposited, and as one proceeds north, successively higher stratigraphic units were directly deposited on Archean basement. Observations from both the Vernon syncline and northern Porter Township, described below, suggest that only part of the Huronian Supergroup succession was deposited in Porter and Vernon townships.

OBSERVATIONS IN AND AROUND THE VERNON SYNCLINE

Ward (1972) suggested that in the northernmost core of the Vernon syncline, rocks of the Matinenda and Ramsay Lake formations were present, even though further south in the syncline, the lowermost Huronian Supergroup units adjacent the Archean contact belong to either the Pecors Formation (in the south) or the Mississagi Formation (north). Ward (1972) based this correlation on stratigraphic position, as he mapped a conglomerate and a quartz arenite unit below rocks he had assigned to the Bruce and Mississagi formations. A complication in the correlation by Ward (1972) was the absence of the intervening Pecors Formation.

The author did find the stratigraphic repetition noted by Ward (1972), but could find no lithological distinctions to suggest that the conglomerate and the quartz arenite were not part of the Bruce and Mississagi formations, respectively. There are two other explanations for the repeated conglomerate–arenite sequence observed by Ward (1972), both of which adequately address the absence of the Pecors Formation. First, the presence of a small-scale drag fold could repeat the sequence locally. Second, as elaborated upon in a subsequent section (*see* "Mississagi–Bruce Contact"), in other parts of the Vernon syncline, there is clear evidence for interfingering of Bruce Formation wacke and conglomerate with clean, cross-bedded quartz arenite of the Mississagi Formation, stratigraphically well above the contact with the Archean basement. Consequently, the repetition observed by Ward (1972) may simply reflect this interfingering of conglomerate and quartz arenite, albeit at the contact with the Archean basement.

The only rock type observed in the Vernon syncline that might have affinity with the Matinenda Formation occurs on the northeast limb of the Vernon syncline (UTM 441408E 5149458N, NAD83, Zone 17). It consists of an unusual, potassium feldspar and granite cobble-rich, clast-supported conglomerate that appears to be locally derived from the Birch Lake granite, with minimal transport based on the angular nature of the clasts and the lath-like nature of many of the feldspar grains. Stratigraphically, this unit does not occur at the margin of the syncline, but occurs above Bruce Formation conglomerate, and was likely related to a small granitic basement high that was exposed during Bruce Formation deposition.

In the outlier north of the Vernon syncline, as one proceeds north, first rocks of the Bruce Formation, then rocks of the Espanola Formation, directly overlie the Archean basement (Marmont 1986; Easton 2004). West of the northernmost part of the Vernon syncline, as noted by Marmont (1986), rocks of the Cobalt Group are in contact with Archean basement, although whether this is a fault, or a depositional contact, or both, cannot be ascertained unequivocally.

Conglomerate and arenite of the Gowganda Formation are observed in direct contact with the Birch Lake granite at UTM 439714E, 5148757N (NAD83, Zone 17), along the western margin of the Vernon syncline. The contact is near vertical. The granite shows no indication of increased deformation as the contact is approached. A thin (10 to 15 cm thick zone) of black-weathering, fine-grained chloritized rock occurs at the contact, overlain by a thicker unit of matrix- and clast-supported conglomerate. In thin section, the fine-grained rock shows no indication of relict mylonitic texture. Chemically, this rock is nearly identical to other Gowganda Formation mudstones higher in the Vernon syncline, and shows no geochemical signature indicative of representing a tectonic mixture of fine-ground granite and sediment. Although the contact has been structurally modified to account for its near-vertical attitude, there is no indication at this locality that the contact is a major shear zone along which several kilometres of structural offset has occurred, as suggested by Mungall and Hanley (2004), based on observations made along the same contact, roughly 1.4 km further south (UTM 438498E, 5147385, NAD83, Zone 17).

OBSERVATIONS IN THE PORTER LAKE AREA

Northeast of Porter Lake, Archean monzogranite is in indeterminate contact with the Huronian Supergroup. The granite forms a topographically high ridge, with 30 to 50 m of relief. There is no indication in the granite of increased deformation as the contact with the Huronian is approached, nor of increased weathering suggesting the presence of a regolith. Regionally, there may be an increase in the abundance of mafic dikes of several different generations proximal to the Huronian contact, as shown on the map of Ginn (1961). The contact between the Archean and the Huronian Supergroup is not exposed; a minimum of 2 to 5 m of cover separates the two units. In all instances, the Huronian Supergroup rocks are found at much lower elevations than the nearest granite outcrops. In this area, a zone of thinly laminated mudstone and siltstone, up to 50 m thick, is located between the granite and quartz arenite of the Mississagi Formation. These mudstones and siltstones have been assigned by the author to the Pecors Formation, based on their lithological and geochemical character. It is possible that this contact is either an inverted growth fault, or a re-activated thrust fault, similar to that described by Jackson (2001) along the Archean–Huronian Supergroup contact in Aberdeen Township.

West of Porter Lake, similar contact relations are observed. The granite forms a topographically high ridge, with 30 to 50 m of relief. Again, there is no indication in the granite of increased deformation as the contact with the Huronian Supergroup is approached, nor of increased weathering suggesting the presence of a regolith. West of Porter Lake, a greater covered zone is present. The closest Huronian Supergroup strata to the contact are quartz arenite outcrops of the Mississagi Formation, although it is possible that some Pecors Formation rocks may underlie the covered interval.

East and southeast of Porter Lake, Ginn (1961) mapped several small, isolated outcrops of granite within a sea of Mississagi quartz arenite. Ginn (1961) regarded these granite bodies as intrusive into the Mississagi Formation, and possibly younger than the Birch Lake granite. The author examined several of these outcrops, and found that they consist of medium- to coarse-grained, monzogranite and protomylonitic monzogranite, similar to the Birch Lake granite exposed north of Porter Lake. At the largest and best exposed outcrop area (UTM 445280E, 5142613N, NAD83, Zone 17), deformation in the granitic rocks is more intense than in the adjacent quartz arenites, suggesting that the granite was deformed prior to quartz arenite deposition. Unfortunately, a covered zone, roughly 1 m wide, separates the nearest granite and quartz arenite outcrops, making this interpretation equivocal. A sample from the same outcrop area is chemically similar to other samples of the Birch Lake granite, although with slightly lower alkali contents (Ba, K, Rb, Sr), which can be attributed to the deformation the rock has experienced. These granite outcrops suggest that east and southeast of Porter Lake, the Mississagi Formation directly overlies Archean granitic basement.

In summary, observations in the Porter Lake area indicate that rocks of the lower Hough Lake and Elliot Lake groups were not deposited in much of northeastern Porter or southern Vernon townships, and that in most of northeast Porter Township, the Mississagi Formation either lies directly on Archean basement, or a thinned horizon (50 to 75 m thick) of Pecors Formation is the lowermost Huronian Supergroup unit.

THE MISSISSAGI–BRUCE FORMATIONS CONTACT

The contact between the Mississagi and Bruce Formation shows considerable variation from south to north across the Porter–Vernon area. This is in contrast to the observations of Card (1978, p.74-75), who noted that the "contact between the Bruce Formation and the underlying Mississagi Formation is generally abrupt and regular with no evidence of erosion or underlying discordance between the underlying Mississagi sandstone and the Bruce conglomerate". Card (1978) did note a few exceptions to this generalization, mainly based on observations by Ginn (1961) from Porter Township.

Figure 13.2 summarizes the observations of the Mississagi–Bruce formations contact made during this study. In the northern part of the Vernon syncline, the contact exhibits little angular discordance, and interfingering of Bruce Formation conglomerate and quartz gritstone with clean, cross-bedded Mississagi Formation quartz arenite is clearly observed (UTM 441916E 5147654N, NAD83, Zone 17). In northern Porter Township, the uppermost Mississagi Formation contains one or more mudstone to siltstone horizons, up to 5 m thick, as well as 5 to 10 m thick zones of thick interbedded mudstone and quartz arenite. There is also evidence for erosional discordance in the upper Mississagi Formation where these shaly units are present. In the vicinity of the Midport fault system, these shaly horizons commonly serve as loci for Sudbury Breccia bodies. In central and southern Porter Township, Bruce Formation conglomerate typically rests in sharp contact with adjacent clean, cross-bedded Mississagi quartz arenite.

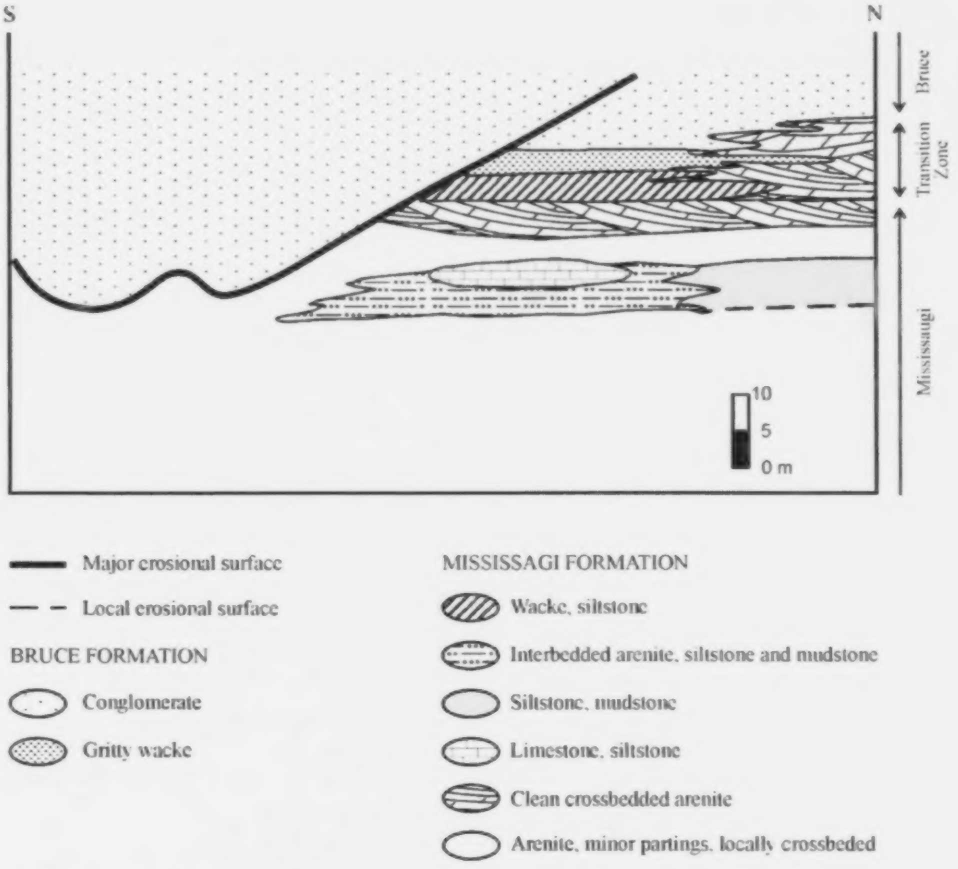

S
N
Bruce
Transition Zone
Mississagi
10
5
0 m
Major erosional surface
Local erosional surface
BRUCE FORMATION
Conglomerate
Gritty wacke
MISSISSAGI FORMATION
Wacke, siltstone
Interbedded arenite, siltstone and mudstone
Siltstone, mudstone
Limestone, siltstone
Clean crossbedded arenite
Arenite, minor partings, locally crossbeded

Figure 13.2. Cartoon illustrating the complex contact relationships between the Mississagi and Bruce formations in the Porter–Vernon area. In the north, the upper Mississagi Formation contains siltstone and mudstone horizons, minor limestone, and locally grades into and/or interfingers with Bruce Formation wackes and conglomerate. In contrast, in the southern part of the area, the Bruce Formation conglomerate is in sharp contact with Mississagi Formation arenite. These differences can be explained by the presence of an erosional surface in the south part of the area that has selectively removed parts of the upper Mississagi Formation, bringing Bruce Formation conglomerate in direct contact with stratigraphically lower parts of the Mississagi Formation.

These disparate observations can be reconciled with increasing amounts of mudstone and, locally, limestone (Easton 2004) being deposited in the upper Mississagi Formation, possibly related to slightly deepening water or transgression to an open marine environment. This depositional environment was interrupted by the sudden influx of the relatively thin, sheet-like Bruce Formation. Initially, in the north, onset of Bruce Formation deposition was relatively calm, resulting in interbedded sheets of conglomerate and wacke and cross-bedded arenites, however, this was quickly replaced by a higher energy regime which downcut into the underlying Mississagi Formation strata, perhaps removing as much as 20 to 40 m of strata *(see* Figure 13.2). It is possible that this erosion was enhanced by channelization along a north-trending structure present along the axis of the present Vernon syncline. Subsequent to Bruce Formation deposition, sedimentation appears to have reverted back to an upper Mississagi Formation style, with deposition of limestone, mudstone and siltstone of the Espanola Formation in a shallow water, low-energy environment.

Several uranium showings have been documented in the study area near the contact between the Mississagi and Bruce formations. Field observations and scintillometer measurements indicate these occurrences are present where mudstone and siltstone horizons are present in the upper Mississagi Formation (*see* "Radiometrics"). As noted by Easton (2004), these fine-grained horizons in the upper Mississagi Formation are rich in uranium- and thorium-bearing minerals such as zircon and monazite. The radioactive elements may have become remobilized where subsequent alteration of the Mississagi Formation has occurred, in part related to major fault systems, such as the Midport fault system, as well as the development of Sudbury Breccia bodies. It is possible that this is a mineralization environment unique to the Porter–Vernon area, due both to the abundance of these fine-grained horizons in the Mississagi Formation compared to other parts of the Southern Province, and to the subsequent alteration and brecciation that may have caused local transport and deposition of uranium and thorium.

THE SERPENT–GOWGANDA FORMATION CONTACT

The Serpent Formation is more widespread, and thicker, than shown by Ward (1972). Furthermore, the contact between the Serpent and Gowganda Formation within the Vernon syncline is very irregular, and is discordant to the orientation of strata beneath the Serpent Formation. Where the contact can be observed (UTM 440605E 5148344N and 440075E 5147784N, NAD83, Zone 17), bedding in the Serpent Formation is at a high angle to bedding in the Gowganda Formation. The thickness of the Serpent Formation underlying the Gowganda Formation is quite varied, ranging from 100 to 400 m. In addition, folding of internal units within the Gowganda Formation results in a westerly oriented geometry, whereas folding of the Serpent Formation results in a northerly geometry. As illustrated in Figure 13.3, these observations can be explained by a model of folding of the Pecors to Serpent formations strata prior to deposition of the Gowganda Formation, most likely along an angular unconformity. A subsequent folding event resulted in the current geometry.

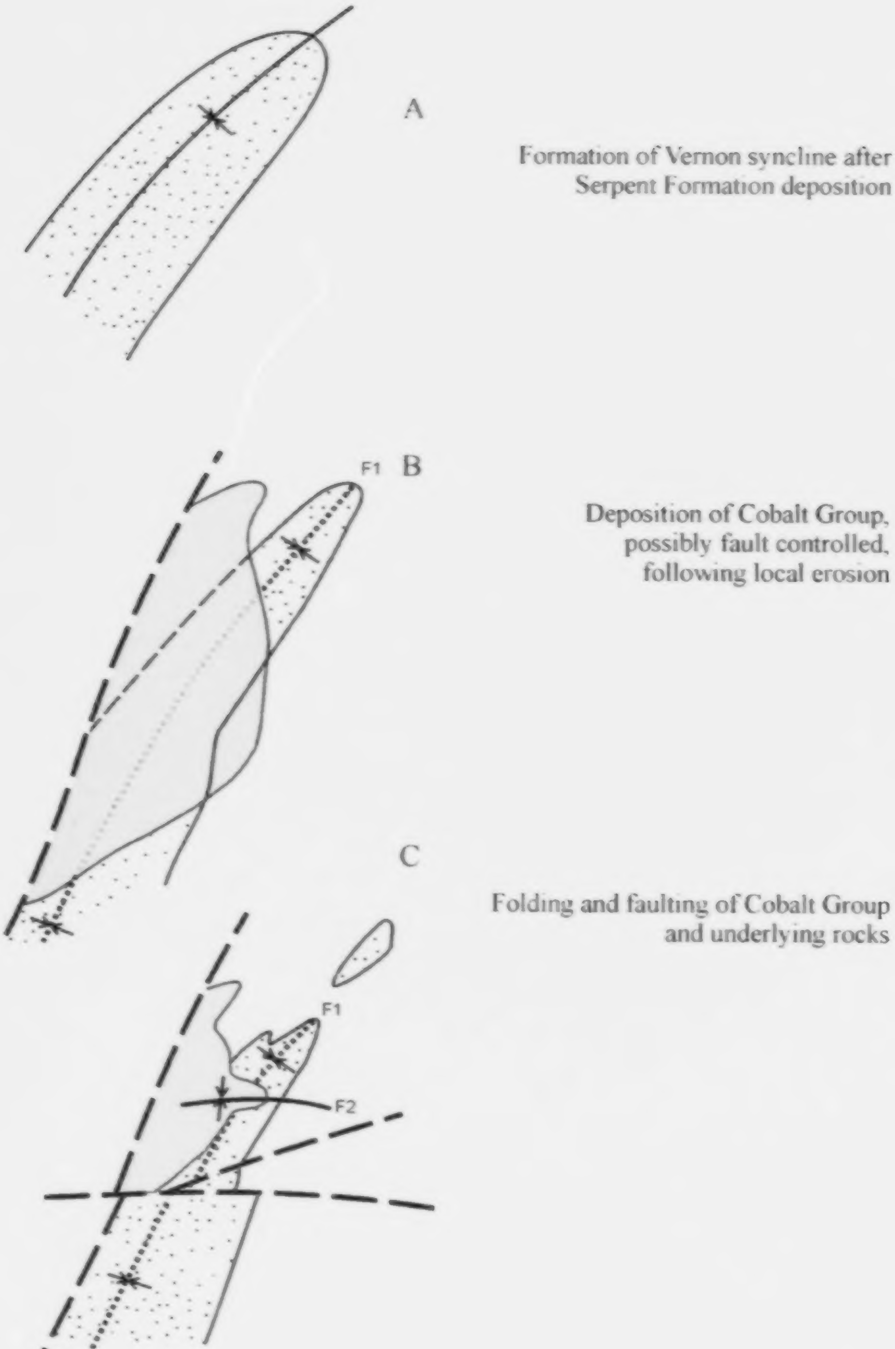

A
Formation of Vernon syncline after Serpent Formation deposition
F1
B
Deposition of Cobalt Group, possibly fault controlled, following local erosion
C
Folding and faulting of Cobalt Group and underlying rocks
F1
F2
F1

Figure 13.3. Cartoon illustrating the possible development of the Vernon syncline. A) Syncline forms following deposition of Serpent Formation, possibly coincident with emplacement of stratiform Nipissing gabbro sills. B) Deposition of Cobalt Group on an eroded surface, possibly controlled by local faulting. C) Folding of Cobalt Group and underlying rocks, possibly coincident with renewed faulting related to regional emplacement of Nipissing gabbro sills and dikes discordant to stratigraphy.

MAP PATTERN AND FOLD GEOMETRY

A curious aspect of the Porter–Vernon area is the abundance of the Mississagi Formation strata in domains 2 and 3, and the generally limited stratigraphic succession (Mississagi–Bruce–Espanola formations), especially if the area has been subjected to only a single folding event, as has been suggested by most past workers (e.g., Ginn 1961; Card 1978). Mapping as part of this study, as well as examination of existing maps on which the fault displacement has been restored, indicates that domains 2 and 3 exhibit a dome and basin geometry indicative of 2 phases of orthogonal-folding (type 1 interference pattern of Ramsay 1967), as illustrated in Figure 13.4. This fold geometry, in conjunction with the observation that the stratigraphically lowest Huronian Supergroup unit in domains 2 and 3 is the uppermost Pecors Formation, explains both the abundance of Mississagi Formation strata and the limited preserved stratigraphic succession in the Porter–Vernon area. The recognition that a fold interference patterns is present in the area is also significant with respect to mineral exploration in the area, in particular, in the siting of drill holes on the limbs of minor fold structures.

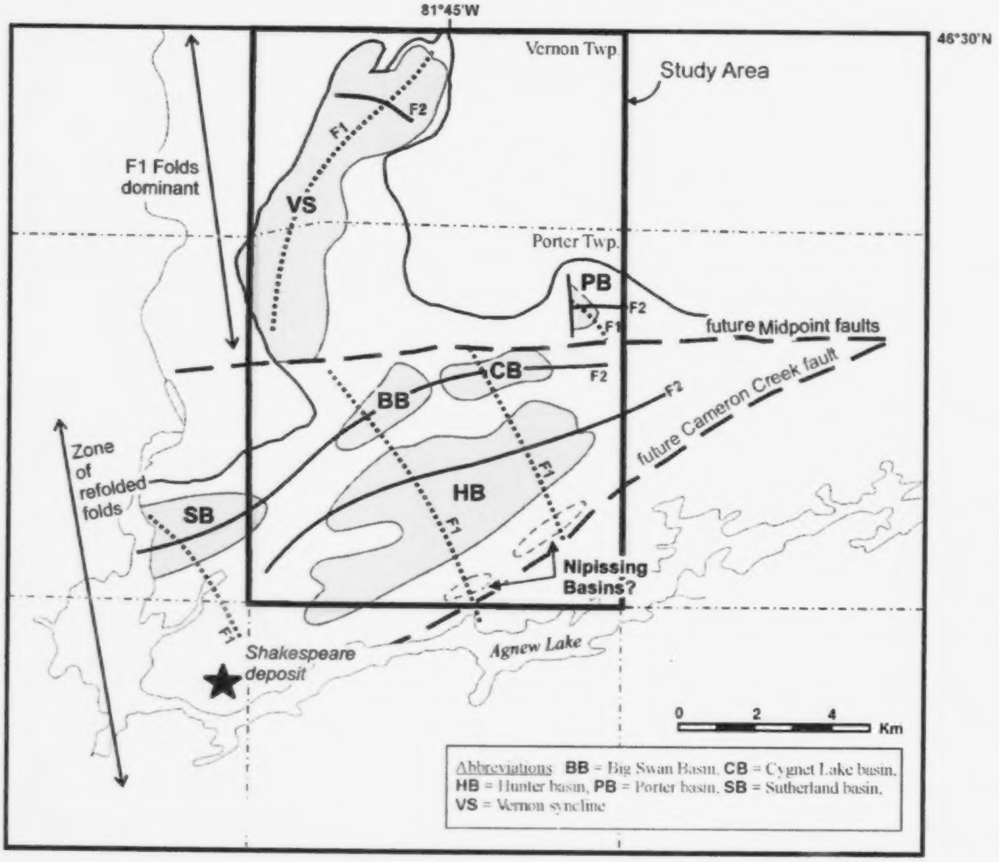

81°45'W
46°30'N
Vernon Twp.
Study Area
F2
F1
F1 Folds dominant
VS
Porter Twp.
PB
F2
F1
future Midpoint faults
CB
F2
BB
F2
future Cameron Creek fault
F1
Zone of refolded folds
HB
F1
SB
Nipissing Basins?
F1
Shakespeare deposit
Agnew Lake
0
2
4
Km
Abbreviations BB = Big Swan Basin, CB = Cygnet Lake basin, HB = Hunter basin, PB = Porter basin, SB = Sutherland basin, VS = Vernon syncline

Figure 13.4. Simplified geological map of the northeast shore of Agnew Lake, showing the distribution of fold styles within Porter and southern Vernon townships. The contact between the Mississagi and Bruce formations has been highlighted to illustrate the fold pattern, and units stratigraphically above the Bruce Formation are shown by a pattern. Between the Cameron Creek and Midport faults, the area is dominated by a dome and basin geometry, indicating the presence of two fold generations, with approximately perpendicular axial planes. North of the Midport fault, the early, north-oriented fold style (F_1) dominates.

TIMING OF FOLDING

Both fold generations are cut by major faults filled with Sudbury Breccia bodies, indicating that folding took place prior to the 1850 Ma Sudbury Event. As the peak of the Penokean orogen in the United States is dated at 1835 Ma (Holm et al. 2001), it becomes problematic whether or not folding of the Huronian Supergroup in the Porter–Vernon area can truly be called Penokean. Folding may, in fact, be as old as 2220 Ma, the age of Nipissing gabbro emplacement in the region. As noted by Easton (2004), some Nipissing gabbro bodies in the Porter–Vernon area are stratigraphically concordant, mostly those that occur in the middle Mississagi Formation or within the Espanola Formation, particularly in the Vernon syncline; whereas others are stratigraphically discordant, such as the major Nipissing gabbro body that hosts both the Shakespeare deposit and the mineralization at the East and Main skarns. Regionally, the discordant Nipissing bodies also cut across rocks of the Cobalt Group. Furthermore, the unusual distribution of map units within the Vernon syncline can be in part explained by early folding (F_1) of the syncline and local erosion at the top of the Serpent Formation prior to Cobalt Group deposition and additional deformation (F_2), as illustrated in Figure 13.3. If this interpretation is correct, then the first phase of folding likely occurred along north-northeast axes, with the second phase occurring along a more westerly axis.

The possibility of 2 distinct folding events in the Southern Province is not new. Easton and Murphy (2002) previously suggested the presence of 2 phases of folding in the Huronian Supergroup east of Sudbury. Jackson (2001) in his structural study of the western Southern Province, did not clearly identify an earlier folding event, although he did report evidence for a pre-Nipissing compressional event, with the main folding event in the Southern Province occurring syn- to post-Nipissing gabbro emplacement. Jackson (2001) also favoured a model similar to the one suggested above, where there were 2 pulses of mafic magma. The first pulse resulted in emplacement of mafic bodies subparallel to Huronian Supergroup strata prior to the main (F_2) folding event, with the second pulse of magma being injected along the axial planes of F_2 folds immediately after folding, at circa 2220 to 2210 Ma.

Nipissing Gabbro

GEOCHEMISTRY

The source magma for the gabbroic intrusions of the Nipissing intrusive suite in the Sudbury area is a tholeiitic, continental flood basalt magma that has been bulk contaminated at its source, prior to ascent into the upper crust (Jobin-Bevans and Keays 2005; Sproule et al. 2005). The magma is PGE-fertile, S-undersaturated, and separated PGE sulphides during normal fractionation, with the sulphides accumulating in orthopyroxene-rich gabbronorites in the lower parts of the intrusions (Jobin-Bevans and Keays 2005). Jobin-Bevans and Keays (2005) report background levels of 20.5 ppm Pd, 12.4 ppm Pt, 91 ppm Cu and 149 ppm Ni for the Nipissing intrusive suite.

At the Shakespeare deposit, which is hosted in a Nipissing gabbro intrusion located adjacent to the southwest corner of the study area, 2 magmatic packages are present, both of which have an age of 2217 Ma (Sproule et al. 2005). A lower package of unmineralized pyroxenite and gabbro and an upper package of mineralized melagabbro, quartz gabbro and quartz diorite. The upper package is chilled against the lower package, and Ni-Cu-PGE mineralization is concentrated at the melagabbro and quartz gabbro contact (Sproule et al. 2005). Palladium, Pt and Ni are depleted in the quartz gabbro and the quartz diorite overlying the mineralized zone (Sproule et al. 2005).

Table 13.1. Geochemical variants of the Nipissing intrusive suite in the study area.

Group (short name)	Rock Name (Jensen rock name in brackets)	Magmatic Affinity	Key Chemical Features	Ni-Cu-PGE	Location
1	Granodiorite (calc-alkaline rhyolite)	Calc-alkaline	SiO_2 >65 wt %		Big Swan, Main skarn
2 (high K and P)	Quartz monzodiorite or quartz monzogabbro (tholeiitic andesite to dacite)	Oceanic Island Basalt	K_2O >2.0 wt % P_2O_5 >0.20 wt % Al_2O_3 >16.5 wt % MgO <2.5 wt % TiO_2 >1.0 wt %		Big Swan, Main skarn
3 (typical)	Gabbro, gabbronorite (high iron tholeiite)	Continental Flood Basalt	Fe_2O_3 >11.0 wt %	Pd>20 ppb, Pt>30 ppb, Cu>70 ppm, Ni>100 ppm	Big Swan, Main skarn, Hanover property, Porter grid, Vernon syncline,
4 (noritic)	Gabbronorite (high magnesium tholeiite)	Continental Flood Basalt	MgO >8.0 wt % CaO >9.0 wt % K_2O <0.6 wt % TiO_2 <0.66 wt % Zr <57 ppm	Pd>20 ppb, Pt>30 ppb, Cu>70 ppm, Ni>100 ppm	Big Swan, East skarn, eastern Porter Township
5 (low Al)	Melagabbro and/or tremolite schist (basaltic komatiite)	Continental Flood Basalt	Al_2O_3 <11.0 wt % SiO_2 >50.5 wt %, TiO_2 <0.66 wt % MgO >11.5 wt % Cr >800 ppm, Zr <55 ppm		Big Swan, East skarn and north of Cygnet pond

The Nipissing gabbro intrusion hosting the Shakespeare deposit appears to be continuous along both limbs of the Porter syncline, although the gabbro does cut across stratigraphy at a shallow angle, being solely hosted in the Mississagi Formation at the Shakespeare deposit, but being emplaced along the Bruce–Espanola formations contact at the Big Swan property in central Porter Township. Most of the intrusion consists of rocks of the lower package only. The upper package of melagabbro, quartz gabbro and quartz diorite is present only locally, most notably at the Main skarn on the Big Swan property.

Preliminary geochemical examination of Nipissing gabbro samples from the study area collected as part of this study, along with samples reported by Turcott (1997) from the Main skarn of the Big Swan property, indicate the presence of at least 5 distinct compositional groups, as summarized in Table 13.1. Although various major element discrimination diagrams distinguish some or all of these groups, the Jensen (1976) diagram appears to work best.

There is considerable brecciation of both the host rocks and the Nipissing intrusive rocks at the Hanover and Big Swan properties, making it difficult to determine if there is a systematic stratigraphic variation between rock types at the different occurrences that might be potentially useful in evaluating mineral potential. Nonetheless, the following observations can be made. Rocks of group 5 and 4, especially group 5, are most closely associated with the development of skarns in the Espanola Formation. This could reflect higher emplacement temperatures associated with these more magnesium-rich rocks. Rocks of group 3 are present from all mineralized properties for which samples are available (Porter grid, Hanover property, Big Swan property Main and East skarns and the Ridge zone). Rocks of group 2 and 1 have so far only been found at the Main skarn of the Big Swan property.

Lightfoot and Naldrett (1996) suggested that key geochemical indices for locating mineralization with the Nipissing gabbro suite are rocks with greater than 9.0 weight % MgO, less than 0.4 weight %

TiO_2, and less than 52 ppm Zr. These criteria target orthopyroxene-rich high-magnesium rocks. Rocks from group 5 and some samples from group 4 (*see* Table 13.1) from the study area fit these criteria. Of particular interest is a sample meeting these criteria that was taken from a Nipissing gabbro intrusion north of Cygnet pond, which intruded a structural basin of Espanola Formation rocks. Thus, both skarn and Nipissing-hosted sulphide mineralization may be expected north of Cygnet pond.

The geochemical indices of Lightfoot and Naldrett (1996), however, did not take into account the Shakespeare deposit style of mineralization. Granodioritic rocks of group 1 are volumetrically small and, consequently, might not be well exposed, but they occur in association with the volumetrically more abundant group 2 gabbros that are characterized by high K and P contents (*see* Table 13.1). Gabbros of group 2 should be identifiable readily in any regional geochemical sampling program and might be an exploration criteria for locating Shakespeare-style mineralization.

Geophysical Properties

MAGNETISM

Granitic rocks of the Birch Lake granite, as well as mafic dikes cutting the granite, gave uniformly low magnetic susceptibility readings (0.10 to 0.80 x 10^{-3} SI). As observed in 2004, magnetic susceptibility readings on rocks of the Huronian Supergroup in domains 2, 3 and 4 were remarkably uniform, and showed no systematic variation with stratigraphic height or stratigraphic unit. The lowest readings were observed in quartz arenite beds (0.00 to 0.10 x 10^{-3} SI), the highest readings in mudstone and siltstone beds (0.20 to 0.50 x 10^{-3} SI). The exception was some matrix-supported conglomerates within the Gowganda Formation that gave average values of 2.5 to 8 x 10^{-3} SI. Gowganda mudstones and clast-supported conglomerates do not show these higher values. Debicki (1990) reported that magnetite is abundant in some matrix-supported conglomerates of the Gowganda Formation in the Sudbury area, and we may be seeing a similar unit in the map area.

Nipissing gabbro bodies were fairly uniform, with average readings of 0.78 x 10^{-3} SI, except where the rocks preserved primary mineralogy, which gave higher readings (1 to 15 x 10^{-3} SI). Sulphide-bearing pyroxene skarn bodies adjacent to Nipissing gabbro intrusions yielded high readings (4 to 50 x 10^{-3} SI), indicating that large sulphide bodies should be detectable by magnetic methods. Sudbury diabase dikes were the only unit to show consistently high readings (25 to 65 x 10^{-3} SI), however, published regional aeromagnetic maps of the map area are too coarse to allow for mapping of individual Sudbury dikes.

RADIOMETRICS

As noted in Easton (2004), the map area lies at the western limit of a high-resolution gamma-ray spectrometric survey of the Sudbury area (Carlson et al. 2004a, 2004b, 2004c). The utility of this survey is limited in Vernon Township because of the greater overburden thickness, but the survey does provide some insight into the geology of Porter Township. In general, the area underlain by Huronian Supergroup rocks in both Porter and Vernon townships exhibits low radiometric values for K, U and Th, at least as far north as the northern tip of the Vernon syncline. In contrast, the areas underlain by Archean metaplutonic rocks in the 2 townships exhibit high K, Th, and U values. Because of the potential utility of the airborne gamma-ray spectrometric survey, a portable spectrometer was rented for part of the summer to obtain radiometric data for the various lithostratigraphic units in the map area and to test the utility, reliability and accuracy of the instrument during the course of regular field work.

Table 13.2. Comparison of scintillometer readings and whole-rock geochemical data from the same rock unit. Note that the scintillometer readings were not always collected from exactly the same spot as the geochemical sample, and that not all readings were taken on the same day.

Sample Number	Easting	Northing	Rock Type	Formation or Unit	Data Source	K (%)	U (ppm)	Th (ppm)	K (cpm)	U (cpm)	Th (cpm)
04RME-0005	446762	5143486	Mudstone	Pecors	Scint	3.1	7.3	13.9	198	54	17
					Chem	***2.73***	***5.9***	***13.8***			
04RME-0012	446307	5142991	Arenite	Sudbury Breccia	Scint	2.1	4.7	5.3	126	28	7
					Chem	***2.6***	***4.7***	***10.4***			
04RME-0023	445668	5141437	Mudstone	Mississagi	Scint	2.2	6.4	12.0	151	48	15
					Chem	***3.7***	***6.6***	***16.1***			
04RME-0024	445668	5141437	Limestone	Mississagi	Scint	0.8	2.7	5.3	59	21	7
					Chem	***0.3***	***1.1***	***4.0***			
04RME-0029	445881	5141097	Siltstone	Mississagi	Scint	4.1	11.4	15.4	267	73	19
			Siltstone	Mississagi	Scint	3.1	16.2	18.6	260	99	25
					Chem	***5.3***	***19.1***	***28.8***			
			Arenite	Mississagi	Scint	2.5	2.9	7.5	134	25	9
					Chem	***2.9***	***1.0***	***3.8***			
04RME-0038	439510	5137234	Conglomerate	Block in Sudbury Breccia	Scintr	0.8	6.0	6.9	84	37	9
					Chem	***1.2***	***4.8***	***11.9***			
04RME-0052	442038	5139031	Mudstone	Espanola	Scint	0.1	4.0	7.5	41	30	10
					Chem	***0.1***	***6.5***	***15.7***			
05RME-0110	440896	5146922	Granite	Birch Lake	Scint	3.5	4.0	23.0	214	58	28
					Chem	***4.6***	***2.1***	***37.3***			

Location data is in UTM Zone 17, and the datum is NAD83. Abbreviations: % - weight percent; Chem – chemistry; cpm – counts per minute; Scint – scintillometer. All data recorded using an Exploranium GR-130 MiniSpec gamma ray spectrometer, serial number 9865, calibrated on March 23, 2005, using an NaI crystal and software version 5V15G. The instrument was stabilized daily, and data was recorded using the assay mode with a 3-minute count time. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

Table 13.2 provides a comparison between the scintillometer data and samples for which whole-rock geochemistry was available at the time of report preparation. In some instances, such as sample 04RME-0005, correspondence between the scintillometer and chemical data is excellent; in other samples, such as sample 04RME-0029, the results are more divergent. Even for sample 04RME-0029, however, the scintillometer data still records the order of magnitude elemental differences between the siltstone and arenite beds in this outcrop. In general, Th shows the most variation of the 3 measured elements, generally being underestimated at low counts (<10 cpm).

Table 13.3 summarizes the results from over 150 scintillometer readings taken on selected rock units from the study area. The ground scintillometer results confirm that the Archean metaplutonic rocks in the 2 townships are characterized by high K, Th, and U values, with 13 non-deformed outcrops giving average values of 3.4% K, 6.8 ppm U and 29.1 ppm Th. Altered granite outcrops had reduced K contents (generally <2.0%). Two granite outcrops in Bigelow Township near the northwest corner of Vernon Township (*see* Table 13.3) had higher Th values than elsewhere in the study area, suggesting that there might be local compositional variations within the Birch Lake granite that could be mapped out with systematic traversing using the scintillometer.

Two historic uranium showings in Porter Township were examined. Survey mode failed to detect any significant hot spots. As a result, assay mode was used on hematite-stained rocks (the most altered rocks) at both showings (*see* Table 13.3). At one-showing, potassium, uranium and thorium were slightly

Table 13.3. Scintillometer results for selected units from the study area.

Sample Number	Easting	Northing	Rock Type	Formation or Unit	Comment	K (%)	U (ppm)	Th (ppm)
Average			Granite	Birch Lake	n=13, non-altered	3.4	6.8	29.1
05RME-0032	437034	5153425	Granite	Birch Lake	High Th	0.7	6.9	**49.7**
05RME-0034	436830	5152896	Granite	Birch Lake	High Th, ***highest Th value of all readings***	4.4	9.9	**88.8**
05RME-0022	445686	5141538	Arenite	Mississagi	Subtype 1, white, massive	2.6	5.4	3.0
05RME-0029	445686	5141538	Arenite	Mississagi	Subtype 1, white, massive	2.5	2.9	7.5
05RME-0273	443525	5139983	Arenite	Mississagi	Subtype 2, reddish, fractured and quartz veined	0.0	0.4	0.0
05RME-0022	445686	5141538	Arenite	Mississagi	Subtype 3, greenish, vein-like alteration layer	4.5	2.7	13.6
05RME-0022	445686	5141538	Arenite	Mississagi	Subtype 3, greenish alteration patch, ***highest U value of all readings***	3.4	**40.1**	**37.4**
05RME-0029	445686	5141538	Arenite	Mississagi	Subtype 3 or 4, greenish layer (siltstone or alteration?)	3.1	16.2	18.6
05RME-0093	443593	5141697	Mudstone	Mississagi	Subtype 4, dark, schistose	3.4	**20.2**	**35.2**
05RME-0065	445134	5140901	Arenite	Mississagi	Uranium showing	1.6	1.5	5.9
05RME-0066	445177	5140831	Arenite	Mississagi	Uranium showing	1.0	1.3	4.1
05RME-0085	446276	5142614	Arenite	Mississagi	Uranium showing	3.4	12.0	17.9
05RME-0086	446279	5142654	Siltstone	Mississagi	Uranium showing	3.6	17.6	16.5
05RME-0086	446279	5142654	Arenite	Mississagi	Uranium showing	1.7	1.9	2.6
05RME-0244	446225	5141431	Gabbro	Nipissing	Typical, greenschist facies	0.7	1.5	1.2
05RME-0244	446225	5141431	Gabbro	Nipissing	Fresh mineralogy	0.7	0.9	1.5
05RME-0245	440985	5138618	Diorite	Nipissing	Diorite phase	0.8	8.9	11.1

Location data is in UTM Zone 17, and the datum is NAD83. Abbreviations: % - weight percent, cpm – counts per minute. All data recorded using an Exploranium GR-130 MiniSpec gamma ray spectrometer, serial number 9865, calibrated on March 23, 2005, using an NaI crystal and software version 5V15G. The instrument was stabilized daily, and data was recorded using the assay mode with a 3-minute count time. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

elevated in a recessive-weathering, fine-grained, hematite-stained bed, however the increased values for all 3 elements in this bed were similar to what is observed in greenish alteration zones that commonly occur in the Mississagi Formation throughout Porter Township.

The Mississagi Formation, which is one of the most areally extensive units in the map area, is also the most complex unit in terms of radiometric signature, with 4 radiometric subtypes being present (*see* Table 13.3), as follows:

1. unaltered arenite with moderate K, and low U and Th contents
2. fractured, altered or veined arenite with low K, U and Th contents
3. brecciated and/or alteration veined, greenish weathering, chlorite and sericite zones, with moderate to high K, U and Th contents
4. mudstone and siltstone beds with moderate K, U and Th contents

Subtype 1 represents unaltered arenite. Subtype 2 is a leached variety, where K, U and Th have likely been removed. In contrast, subtype 3 results in K, U and Th enrichment, possibly resulting from redeposition of the elements leached from subtype 2. Subtype 4 has higher K, U and Th contents resulting from the higher clay component in the original sediment, and is broadly similar in K, U, and Th contents to other mudstone units in the area, such as the Pecors Formation.

Arenites of subtype 3 are variably cut by Sudbury breccia zones, the matrix of which alters to a pale greenish mixture of chlorite and sericite, as well as similar, clast-absent, greenish, chlorite and sericite alteration veinlets and patches. In the past, some of these zones have been mapped as finer grained partings in the arenites. There are, however, discrete, thin siltstone beds locally within the Mississagi Formation, although sometimes it is difficult to distinguish the true sedimentary beds from these alteration veins. From a radiometric perspective, both the veinlets (subtype 3) and the siltstone beds (subtype 4) are similar, with both showing an increase in K, U and Th content (*see* Table 13.3) compared to typical Mississagi arenite (subtype 1).

As reported in Easton (2004), some samples of Mississagi Formation siltstone (subtype 4) contained anomalous contents of high-field strength elements that are typically associated with heavy mineral concentrations (samples 04RME-0029 and 04RME-0122, *see also* Easton 2004, Table 13.2). Adjacent quartz arenite beds (samples 04RME-0053 and 04RME-0135, respectively, *see also* Easton 2004, Table 13.2) show no such enrichment. Thus, the higher U and Th contents measured in the siltstone beds may, in part, reflect the abundance of U- and Th-bearing phases, such as zircon and monazite, in these beds, in addition to an original higher clay mineral content.

Mafic rocks of all types within the study area generally yield low values for all 3 elements, as illustrated by samples of Nipissing gabbro in Table 13.3. Dioritic phases of the Nipissing gabbro suite have higher U and Th contents (*see* Table 13.3), as might be expected due to their more differentiated character.

The scintillometer data provides some explanation for the airborne radiometric anomalies described in Easton (2004), as elaborated upon below.

1. K, U and Th highs (A, Bk and Bu, *see also* Easton 2004, Figure 13.3). These anomalies are broadly associated with the Mississagi and Bruce formations contact. In both these areas, siltstone and mudstone beds are present in the upper Mississagi Formation near the Bruce Formation contact, and both areas lie in a broad zone of brecciation and alteration associated with the Midport fault system. Both the presence of siltstone (subtype 4) and brecciation and alteration (subtype 3) result in increased K, U and Th within Mississagi Formation strata, and these anomalies likely reflect the combination of these 2 processes.
2. Moderate K highs associated with U highs (C and D, *see also* Easton 2004, Figure 13.3). These anomalies are spatially associated with the East and North Cu-Ni skarn zones, and an area of potential skarn mineralization in northeast Porter Township. Scintillometer readings of all rock units associated with the skarns; namely, the Espanola and Serpent formations, the skarn rocks, and the adjacent Nipissing gabbro all have low K, U and Th contents, and there is no indication of any K or U mobilization on a small-scale at individual skarns. It is possible that the regional anomalies may reflect local anomalies in neighbouring Mississagi and Bruce formations units, resulting from either an abundance of siltstone and mudstone in the Mississagi Formation or brecciation and alteration, or both. In this respect, it should be noted that the Hanover, East and North skarns are proximal to a large, post-skarn formation, regionally continuous zone of brecciation.
3. K and U highs, in some cases associated with moderate Th highs (E to L, *see also* Easton 2004, Figure 13.3). Some anomalies are linear with a northeast orientation. The majority of these highs are underlain by rocks of the Mississagi Formation, near known uranium occurrences. Typically, the known uranium occurrences are located on the flanks of the anomalies, not the

centres. These anomalies appear to be related mainly to subtype 3, that is, brecciation and localized alteration within the Mississagi Formation.

In summary, the scintillometer was easy to use and operate, provided reliable data, and was of great assistance in interpreting the various airborne radiometric anomalies and in understanding the geology of specific map units, such as the Mississagi Formation.

MINERALIZATION

Nickel-Copper-Platinum Group Elements

Several areas of Ni-Cu-PGE mineralization have been previously identified in Porter Township, hosted in both Nipissing gabbro and skarn developed in Espanola Formation limestone and siltstone (Table 13.4). These include the Hanover, East, Main and Ridge skarns, located immediately north of the hydro line in central Porter Township (*see* Figure 13.1). Nickel-copper-PGE mineralization has been observed within Nipissing gabbro in contact with Mississagi Formation quartz arenite west-southwest of Sutherland Lake, in Nipissing gabbro west of O'Brien Lake, and in the Bye Zone located at the Porter–Dunlop township boundary. Table 13.4 provides a summary of the best assay results reported from these occurrences, as compiled from the assessment files in the Sudbury Resident Geologist's Office. All of these occurrences are associated with stratigraphically discordant Nipissing gabbro intrusions.

Gold and Copper

A grab sample collected from a pyroxene skarn horizon from the Big Swan property, Main skarn (UTM 440892E, 5138607N, NAD83, Zone 17), assayed 690 ppb Au, 556 ppm Cu, and 104 ppm As. This is the best result obtained from the various skarn samples collected by the author in 2004 and 2005.

Table 13.4. Summary of Cu-Ni-PGE occurrences hosted in or near Nipissing gabbro in Porter Township.

Name	Easting NAD83	Northing Zone 17	Reported Values	Assessment File Number
Big Swan Property, Brunne PGM (East skarn)	442214	5139227	8.55 g/t Pd, 11.7 g/t Pt, 0.34 g/t Au, 0.15 wt % Cu, 0.14 wt % Ni over 1.0 m	Porter SP-007, SP-011
Big Swan Property, Ridge	441810	5139370	1.48 g/t Pd+Pt+Au, with 1.22 g/t Pd, 0.35 wt % Cu	Porter SP-007, 011
Big Swan Property, Main skarn	440859	5138646	186 ppb Au, cpy and po present	Porter SP-007, SP-011
Hanover	~439472	5137217	>40 ppb Pd+Pt in soil surveys, grab samples of 713 ppb Au and 224 ppb Pt+Pd+Au	Porter SP-007, SP-011
Porter Grid	~437600	5139040	No assay data reported, cpy and po present	
O'Brien Lake	~437800	5138700	15.6 g/t Pd+Pt. Best grab sample 14220 ppb Pd, 1439 ppb Pt, 635 ppb Au, 0.28 wt % Cu.	Porter SP-011, Dunlop SP-007
Bye Zone	~435750	5137450	8.8 g/t Pd+Pt, 7.5 g/t Au. Best grab sample 5439 ppb Pd, 1468 ppb Pt, 735 ppb Au, 1.9 wt % Cu.	Dunlop SP-007

A black slate, located within a shear zone in the Mississagi Formation west of Big Hunter Lake (UTM 439232E, 5135884N, NAD83, Zone 17), assayed 378 ppm Cu, and was also anomalous with respect to Au, Pd and Pt (27, 13 and 7 ppb, respectively).

Lead-Zinc

Several samples collected for routine geochemical analyses yielded unexpected metal results. A black shale from the Mississagi Formation in east-central Porter Township (UTM 445997E 5141380N, NAD83, Zone 17) contained 383 ppm Pb and 125 ppm Zn. This sample was located along a powerline, and, thus, it is possible that the high Pb could be an anthropogenic effect, however, a sample from an adjacent arenite bed only contained 32 ppm Pb and 21 ppm Zn, suggesting that the high Pb value is reliable. Another shale, this time from the Espanola Formation north of Cygnet Lake (UTM 443710E 5141481N, NAD83, Zone 17), assayed 105 ppm Pb and 87 ppm Zn, which is highly anomalous when compared to values of less than 10 ppm typically found for both elements in other Espanola Formation samples from the Porter–Vernon area. These values suggested that shaly horizons within both the Mississagi and Espanola Formations should be more routinely assayed for Pb and Zn.

Uranium and Iron Oxide-Copper-Gold Mineralization

The majority of significant uranium occurrences within the Southern Province are hosted in the Matinenda Formation (Robertson and Gould 1983). The apparent absence of Matinenda Formation strata in domains 2, 3 and 4 of the Porter–Vernon area would appear to limit the uranium potential of this area. A few small uranium occurrences have been reported from Porter Township near the Mississagi–Bruce formations contact, as discussed in "Radiometrics". As noted by Easton (2004), and confirmed in additional samples collected in 2005, shaly horizons within the Mississagi Formation contain high values of high-field strength elements, most notably Zr, but also Hf, Rb, Th, U, and Y. The occurrence of these elements in shaly horizons rather than in heavy mineral lags within the cross-bedded quartz arenite beds in the Mississagi Formation has yet be explained. In this regard, it is worth noting that these shaly horizons are the locus for alteration within the Mississagi Formation, and it is possible that fluids associated with alteration may be one reason why these horizons are rich in high-field strength elements.

As noted in "Radiometrics", the Mississagi Formation shows evidence for widespread regional alteration that appears to be in part fault controlled. This alteration has mobilized a wide variety of elements, including silica, K, U, and Th. Iron oxide-copper-gold (IOGC) mineralization is commonly associated with large-scale regional alteration patterns, and it is possible that the alteration observed within the Mississagi Formation may be the result of an IOGC mineralization event.

SUMMARY

1. Throughout much of the Porter–Vernon area, the Mississagi Formation rests directly on Archean basement, which consists mainly of medium- to coarse-grained granite.
2. A set of west-trending andesitic dikes, emplaced between 2475 and 1850 Ma, is newly reported from the Porter–Vernon area.
3. The Archean basement is similar west and east of the Vernon syncline, suggesting no significant fault displacement occurred within the basement across the syncline.

4. From south to north, progressively higher units within the Huronian Supergroup rest on Archean basement.
5. The Bruce Formation either down cut into the Mississagi Formation during deposition, or was deposited on an angular unconformity developed on the Mississagi Formation.
6. The Gowganda Formation in the Vernon syncline was deposited on an angular unconformity developed on the Serpent Formation. Folding of pre-Cobalt Group strata may also have occurred prior to Gowganda Formation deposition.
7. Two phases of folding have affected the Huronian Supergroup in the Porter–Vernon area, forming a dome and basin interference pattern. Both phases of folding likely occurred pre- or syn-emplacement of Nipissing gabbro bodies in the area (circa 2220 to 2210 Ma). Folding occurred prior to the Sudbury Event at 1850 Ma.
8. 5 geochemical subtypes are present within Nipissing gabbro intrusions within the Porter–Vernon area. At least 2 different subtypes are associated with Ni-Cu-PGE mineralization. To date, Ni-Cu-PGE mineralization in the area has only been reported from stratigraphically discordant Nipissing gabbro bodies.
9. Quartz arenites of the Mississagi Formation have been subjected to a variety of alteration, much of it localized along major fault systems that cut across the Porter–Vernon area.
10. Most map units in the Porter–Vernon area are characterized by low magnetic susceptibilities ($<0.8 \times 10^{-3}$ SI).
11. Shaly units in the upper Mississagi Formation locally are anomalous in Pb, Zn and U.

REFERENCES

Card, K.D. 1978. Geology of the Sudbury–Manitoulin area, districts of Sudbury and Manitoulin; Ontario Geological Survey, Report 166, 238p.

Carson, J.M., Holman, P.B., Ford, K.L., Grant, J.A. and Shives, R.B.K. 2004a. Airborne gamma ray spectrometry compilation, potassium, Ontario; Geological Survey of Canada, Open File 4550, scale 1:2 000 000.

——— 2004b. Airborne gamma ray spectrometry compilation, equivalent uranium, Ontario; Geological Survey of Canada, Open File 4551, scale 1:2 000 000.

——— 2004c. Airborne gamma ray spectrometry compilation, equivalent thorium, Ontario; Geological Survey of Canada, Open File 4552, scale 1:2 000 000.

Collins, W.H. 1938. Espanola sheet; Geological Survey of Canada, Map 291A, scale 1:126 720.

Debicki, R.L. 1990. Stratigraphy, paleoenvironment and economic potential of the Huronian Supergroup in the southern Cobalt Embayment; Ontario Geological Survey, Miscellaneous Paper 148, 154p.

Easton, R.M. 2004. Reconnaissance study of the geology and mineral potential of Porter and Vernon townships, Southern Province; *in* Summary of Field Work and Other Activities, Ontario Geological Survey, Open File Report 6145, p.13-1 to 13-13.

Easton, R.M. and Murphy, E. 2002. Precambrian geology of Street Township, District of Sudbury; Ontario Geological Survey, Open File Report 6078, 149p.

Fairbairn, H.W., Hurley, P.M. and Pinson, W.H. 1960. Mineral and rock ages at Sudbury–Blind River, Ontario; Geological Association of Canada, Proceedings, v.12, p.41-66.

Ginn, R.M. 1960. The relationship of the Bruce Series to the granites in the Espanola area; unpublished PhD thesis, University of Toronto, Toronto, Ontario, 179p.

——— - 1961. Geology of Porter Township; Ontario Department of Mines, Geological Report 5, 36p.

Holm, D.K., Schneider, D.A., O'Boyle, C., Hamilton, M.A., Jercinovic, M.J. and Williams, M.L. 2001. Direct timing constraints on Paleoproterozoic metamorphism, southern Lake Superior region: results from SHRIMP and EMP U-Pb dating of metamorphic monazites; Geological Society of America, Abstracts with Programs, v.33, no.6, p.A-401.

Jackson, S.L. 2001. On the structural geology of the Southern Province between Sault Ste. Marie and Espanola, Ontario; Ontario Geological Survey, Open File Report 5995, 55p.

Jensen, L.S. 1976. A new cation plot for classifying subalkalic volcanic rocks; Ontario Division of Mines, Miscellaneous Paper 66, 22p.

Jobin-Bevans, L.S. and Keays, R.R. 2005. Geochemistry of the River Valley intrusion and the Nipissing gabbro suite, Sudbury, Ontario: implications for ore forming processes; Extended Abstracts, 10th International Platinum Symposium, August 8-11, 2005, Oulu, Finland, p.133-136.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D. and Nakamura, E. 1987. Precise U-Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *in* Mafic dyke swarms, Geological Association of Canada, Special Paper 34, p.147-152.

Lightfoot, P.C. and Naldrett, A.J. 1996. Petrology and geochemistry of the Nipissing gabbro: exploration strategies for nickel, copper, and platinum group elements in a large igneous province; Ontario Geological Survey, Study 58, 81p.

Marmont, C. 1986. Geology of Tofflemire, Venturi, and Vernon townships, District of Sudbury; Ontario Geological Survey, Open File Report 5624, 86p.

Mungall, J.E. and Hanley, J.J. 2004. Origins of outliers of the Huronian Supergroup within the Sudbury Structure; Journal of Geology, v.112, p.59-70.

Ramsay, J.G. 1967. Folding and fracturing of rocks; McGraw–Hill, New York, 568p.

Robertson, J.A. and Gould, K.L. 1983. Uranium and thorium deposits of northern Ontario; Ontario Geological Survey, Mineral Deposits Circular 25, 152p.

Rousell, D.H. and Long, D.G.F. 1998. Are outliers of the Huronian Supergroup preserved in structures associated with the collapse of the Sudbury impact crater?; Journal of Geology, v.106, p.407-419.

Sproule, R.A., Lesher, C.M., Sutcliffe, R. and Tracanelli, H. 2005. Nipissing-aged Ni-Cu-PGE mineralization in the Shakespeare intrusion; Extended Abstracts, 10th International Platinum Symposium, August 8-11, 2005, Oulu, Finland, p.239-242.

Sutcliffe, R.S. 2003. Shakespeare nickel-copper-PGM deposit: a flow-through financed exploration success; Speaker Abstracts, Northeastern Ontario Mines and Minerals Symposium, April 15-16, 2003, Haileybury, Ontario, p.21-22.

Turcott, M.B. 1997. Au-in-skarn mineralization in the Paleoproterozoic Big Swan property, northeastern Ontario, Canada, Porter Twp., Sudbury Mining District; OPAP technical report for the 1997 Work Prorgram; Sudbury Resident Geologist's office, Porter Township, assessment file Porter SP-006, 65p., plus appendices.

Ward, R.C. 1972. Geology of the Huronian Supergroup in the Shiner syncline, Vernon Township, Sudbury District, Ontario; unpublished MSc thesis, Bowling Green State University, Bowling Green, Ohio, 150p.

14. Project Unit 05-001. 10th International Platinum Symposium: Insights Relevant to Ni-Cu-PGE Mineral Exploration in Ontario

R.M. Easton[1] and T.R. Hart[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The 10th International Platinum Symposium, which involved all aspects of the study of the platinum group elements (PGE), was held August 7–11, 2005 in Oulu, Finland, and brought together over 200 geoscientists from over 25 countries. In addition to technical presentations, the conference was also host to several workshops and fields trips related to exploration for platinum group elements. The Ontario Geological Survey was represented at the conference by 2 geoscientists.

- R.M. Easton, because of his work on PGE mineralization in rocks of the East Bull Lake intrusive suite in the Sudbury area, and
- T.R. Hart, because of his work on PGE mineralization in the Lake Nipigon area.

This report provides a summary of the knowledge gained from the technical programme, the workshops, and the field trips of direct relevance to PGE exploration in Ontario. This report is divided into 2 parts. Part 1 focusses on the rocks of the East Bull Lake intrusive suite, in large part because of the presence of contemporaneous mafic intrusive rocks in Finland, which have been the subject of previous comparisons with Ontario (e.g., Heaman 1997; Vogel et al. 1998). Part 2 discusses lessons of broader relevance to all aspects of PGE exploration.

PART 1. GEON 24 LAYERED MAFIC INTRUSIONS IN NORTH AMERICA AND FENNOSCANDIA: ARE EXISTING COMPARISONS OVERSIMPLIFIED?

Several workers (e.g., Amelin, Heaman and Semenov 1995, Heaman 1997, Vogel et al. 1998) have suggested that Geon 24 mafic intrusive rocks at the edge of the Superior craton in Canada (Figure 14.1) and the Karelian craton in Fennoscandia are genetically related (Figure 14.2), with resultant implications for mineral exploration and tectonic correlation. These workers, however, only considered the correlation of the Geon 24 mafic intrusive rocks, and did not make any direct comparisons with the age of the basement that hosts these mafic intrusions, or the age of the metasedimentary rocks that overlie them. Consequently, this correlation is re-examined herein, based both on improvements in our understanding of the geologic history of the southern Superior craton, as well as first-hand observations of the Geon 24 mafic intrusions in Fennoscandia.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.14-1 to 14-14.

© Queen's Printer for Ontario, 2005

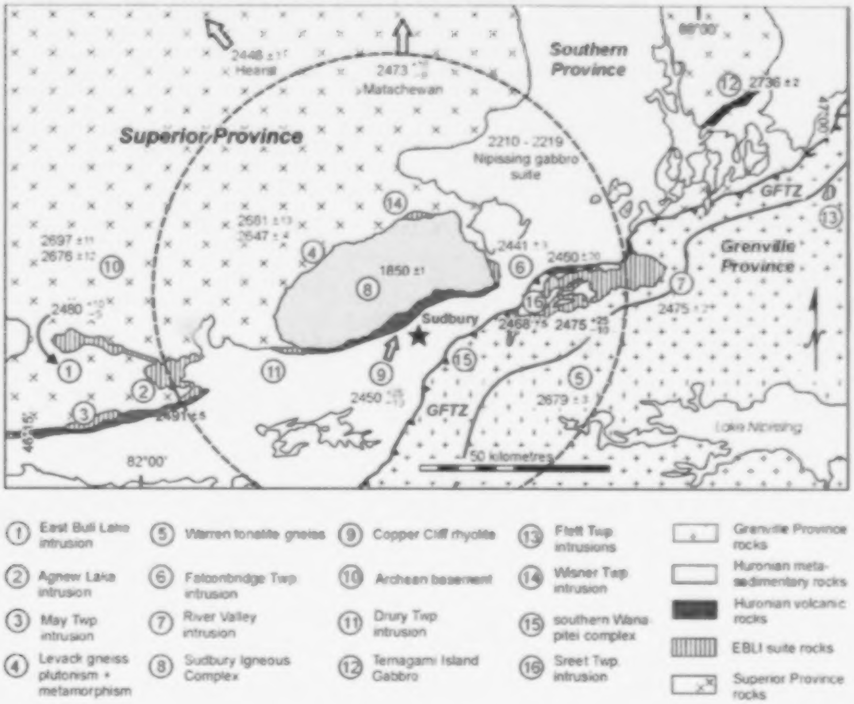

Southern Province
Superior Province
Grenville Province
2448 ±11 Hearst
2473 +16/−9 Matachewan
2210 - 2219 Nipissing gabbro suite
2736 ±2
GFTZ
2681 ±13
2647 ±4
2697 ±11
2676 ±12
1850 ±1
2441 ±1
2460 ±20
2480 +10/−5
Sudbury
2468 ±5
2475 +25/−10
2475 ±2
2450 +25/−10
2679 ±3
2491 ±5
Lake Nipissing
82°00'
46°15'
80°00'
47°00'
50 kilometres
① East Bull Lake intrusion
② Agnew Lake intrusion
③ May Twp intrusion
④ Levack gneiss plutonism + metamorphism
⑤ Warren tonalite gneiss
⑥ Falconbridge Twp intrusion
⑦ River Valley intrusion
⑧ Sudbury Igneous Complex
⑨ Copper Cliff rhyolite
⑩ Archean basement
⑪ Drury Twp intrusion
⑫ Temagami Island Gabbro
⑬ Flett Twp intrusions
⑭ Wisner Twp intrusion
⑮ southern Wanapitei complex
⑯ Sreet Twp intrusion
Grenville Province rocks
Huronian meta-sedimentary rocks
Huronian volcanic rocks
EBLI suite rocks
Superior Province rocks

Figure 14.1. Distribution of U/Pb zircon ages from Neoarchean and Paleoproterozoic rocks in the Sudbury area, and distribution of East Bull Lake intrusive suite bodies. Dashed circle indicates 125 km radius from a point central to the Sudbury Structure, most intrusions lie within this radius. Sources: 1, 2, 8, 9) Krogh, Davis and Corfu 1984; 4) Wodicka and Card 1995; Krogh, Davis and Corfu 1984; 5) Chen, Krogh and Lumbers 1995; 6 and 10) Prevec 1993; below and above circle 16, Corfu and Easton (2000). Age of Hearst and Matachewan dikes *from* Heaman (1997).

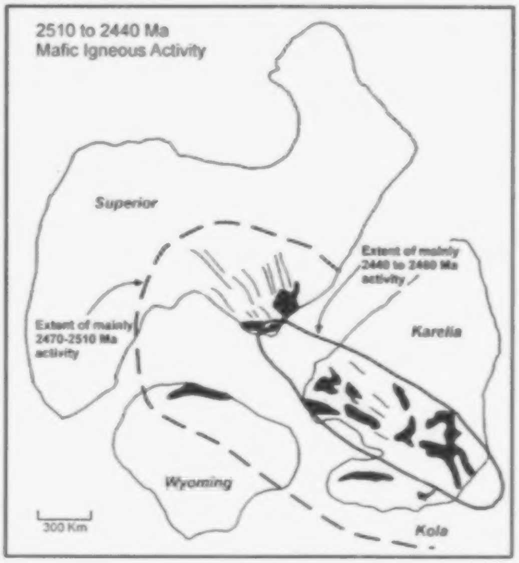

2510 to 2440 Ma
Mafic Igneous Activity
Superior
Extent of mainly 2440 to 2460 Ma activity
Extent of mainly 2470-2510 Ma activity
Karelia
Wyoming
Kola
300 Km

Figure 14.2. Continental reconstruction at 2450 Ma involving the Superior, Wyoming and Karelian cratons. Note the possible presence of an older, broader belt of activity, and a younger, centralized belt of activity. *Modified from* Heaman (1997).

Data Considerations

First, a few words on the respective geoscience databases for Ontario and Fennoscandia. In Ontario, knowledge of the Geon 24 intrusions is based largely on field-based mapping, petrological and geochemical studies, as summarized by James et al. (2002) and Easton, Jobin-Bevans and James (2004). These mafic intrusions are well exposed, with outcrop exposure in the range of 20 to 50%. Stratigraphic sections are mainly field measured, and commonly composite. Petrographic and geochemical data are available from all of the main stratigraphic units. Detailed geochemical and petrologic studies along single stratigraphic transects through the intrusions are rare or non-existent. Geochronological data for Ontario is based mainly on near concordant to concordant, single-grain, U/Pb dating of zircon and/or baddeleyite. Although the Neoarchean basement to the mafic intrusions has not been studied in detail, its age and general composition is known. A single, uniform, stratigraphic framework exists for the metasedimentary rocks of the Huronian Supergroup throughout the Southern Province.

In contrast, outcrop exposure in Finland is much more limited, ranging from 1 to 10%, thus, much of the knowledge of the form and variation in rock types in the Geon 24 mafic intrusions is based on interpretation of geophysical surveys. In addition, detailed knowledge of these intrusions is largely the result of study of samples collected from both research and exploration drill holes through these intrusions. This allows for better documentation of geochemical, mineralogical and mineralization variation with stratigraphic height, but with less control on the regional distribution of rock units. The presence of drill core has meant that Fennoscandian researchers have utilized changes in cumulate mineralogy in order to subdivide the intrusions into different map units. This is in marked contrast to Ontario, where the field-based approach has meant that subdivision of the intrusions into map units is based mainly on macroscopic changes in rock type. Geochronological data for Finland is mainly based on discordant, multi-grain, U/Pb dating of zircon and/or Nd/Sm whole-rock dating (e.g., Perttunen and Vaasjoki 2001), although near-concordant, single-grain U/Pb data are presented in Amelin, Heaman and Semenov (1995). Although the geochronological data from Finland are sufficiently accurate to show that there are 2 distinct age groups of intrusions, currently, the data are not sufficiently precise to allow for correlation between individual bodies (e.g., are some bodies dismembered large intrusions or are they separate intrusions?) or to determine if there are distinct age differences within parts of individual intrusions, as suggested by some of the existing data (e.g., between gabbronorite and anorthosite phases of the Mt. General'skaya intrusion).

In many cases, the amount of exploration data for the Geon 24 mafic intrusions in Fennoscandia is much larger than for the equivalent rocks in Ontario, with the possible exception of the Dana Lake area of the River Valley intrusion. For example, there are over 24 000 m of diamond drilling, low-altitude airborne geophysical surveys, and magnetic, electromagnetic, very-low frequency resistivity, induced polarization and gravimetric surveys for the Koillismaa complex in Finland (Iljina et al. 2005).

In part because of lack of exposure, the basement to the Fennoscandian mafic intrusions is not well known. Paleoproterozoic metasedimentary and metavolcanic rocks that overlie the Geon 24 intrusions in Fennoscandian are grouped into several "schist belts", each with a unique stratigraphy (e.g., Hanski 2001). Correlation of units between these "schist belts" is difficult, and there is no consensus on how the different stratigraphic units correlate with one another.

Superior Craton in Geon 24

The Paleoproterozoic East Bull Lake intrusive suite (Easton 1999; James et al. 2002) consists of several bodies of mainly gabbronorite to gabbroic anorthosite that occur along the southern margin of the Superior craton between Elliot Lake and the Ottawa River (*see* Figure 14.1). The three largest bodies are the River Valley, the East Bull Lake and Agnew Lake intrusions, emplaced between ~2491 and 2475 Ma.

The distribution of East Bull Lake intrusive suite bodies approximates the base of the Huronian Supergroup (*see* Figures 14.1 and 14.3). Contact relationships between rocks of the East Bull Lake intrusive suite and the Huronian are either faulted or equivocal, thus, it is not known if the East Bull Lake intrusive suite intruded the Huronian, or was unconformably overlain by it, or both.

Emplacement of the East Bull Lake intrusive suite, subsequent eruption of Huronian volcanic rocks, and formation of the depositional basin later filled by Huronian Supergroup sediments is attributed by most authors (*see* summary in Easton 2003) to an intracontinental rifting event resulting from a mantle-plume centred near Sudbury. A suite of igneous rocks (hereafter called the "rifting suite") records this plume-induced rifting event; from oldest to youngest, they are

1. The East Bull Lake intrusive suite
2. Elliot Lake Group volcanic and minor plutonic rocks, e.g., the Elsie Mountain, Stobie and Copper Cliff formations, May Township volcanic rocks, and minor synvolcanic mafic intrusions (~2490 to 2450 Ma). Volcanic rocks of the Elliot Lake Group constitute the lowermost of 4 stratigraphic groups in the Huronian Supergroup
3. Matachewan (2473 Ma) and Hearst (2446 Ma) mafic dike swarms (Heaman 1997)

Current data suggest 2 magmatic pulses.

- A mafic-dominated magmatic pulse at ~2475 to 2490 Ma, represented by the East Bull Lake intrusive suite, the Matachewan dikes, and the mafic part of the Elliot Lake Group; and
- A felsic-dominated magmatic pulse at ~2450 Ma, represented by felsic volcanic rocks of the Elliot Lake Group, related granitic intrusions, and the Hearst dikes.

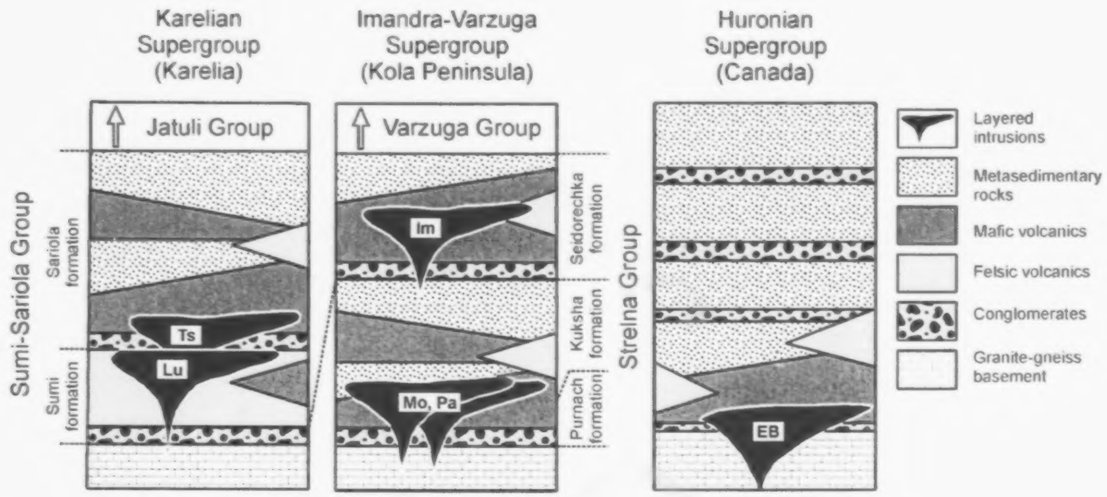

Karelian Supergroup (Karelia)
Imandra-Varzuga Supergroup (Kola Peninsula)
Huronian Supergroup (Canada)
Jatuli Group
Varzuga Group
Sumi-Sariola Group
Sariola formation
Sumi formation
Ts
Lu
Im
Mo, Pa
Seidorechka formation
Kuksha formation
Purnach formation
Strelna Group
EB
Layered intrusions
Metasedimentary rocks
Mafic volcanics
Felsic volcanics
Conglomerates
Granite-gneiss basement

Figure 14.3. Simplifed stratigraphic columns (not to scale) for the Paleoproterozoic supracrustal sequences in Karelia, the Kola Peninsula, and the southern Superior Province. Abbreviations: EB = East Bull Lake intrusive suite (~2475-2491 Ma), Im = Imandra lopolith (2441 Ma), Lu = Lukkulaisvaara pluton (2442 Ma), Mo = Monchegorsk pluton (2504 Ma), Pa = Pana Tundra pluton (2502 Ma), Ts = Tsipringa pluton (2441 Ma). *Adapted from* Amelin, Heaman and Semenov (1995).

Rocks of the East Bull Lake intrusive suite in the Southern Province are metamorphosed at greenschist facies, whereas rocks of the suite in the Grenville Province are metamorphosed at upper amphibolite facies. To date, Ni-Cu-PGE mineralization from the East Bull Lake intrusive suite is all found within a contact-style environment, commonly associated with breccia zones within the mafic intrusions (e.g., James et al. 2002; Easton, Jobin-Bevans and James 2004).

Basement to the East Bull Lake intrusive suite consists of Neoarchean metaplutonic rocks ranging in age from 2680 to 2640 Ma (Prevec 1993; Easton 2000, 2003). Contact relationships with metasedimentary rocks of the Huronian Supergroup are generally faulted, or poorly exposed.

Karelian Craton in Geon 24

Two distinct groups of mafic intrusions occur in the Karelian craton (Vogel et al. 1998). An older group of mafic intrusions, characterized by low Ti and Cr contents, is dominated by gabbronorite and leucogabbronorite, although a few intrusions contain thicker sequences of olivine melagabbros. The older group intrusions range in age from 2501 to 2502 Ma and are geographically restricted to the Kola Peninsula (Figure 14.4)(Amelin, Heaman and Semenov 1995; Vogel et al. 1998). The older intrusions, which include the Mt. General'skaya, Monchegorsk, and Fedorova–Pana Tundra plutons (*see* Figure 14.4), are floored by Archean granitic or gneissic rocks, with their hangingwalls composed of mafic metavolcanic rocks and conglomerates of the lowermost Strelna Group (*see* Figure 14.3). Intrusions of this older group closely resemble the intrusions of the East Bull Lake intrusive suite in terms of composition, age, and relative stratigraphic position (*see* Figure 14.3).

The younger group of intrusions, contain Cr-poor and Cr-rich subgroups, as described by Vogel et al. (1998). The Cr-poor intrusions are dominated by gabbronorite and leucogabbronorite, whereas, the Cr-rich intrusions contain much higher proportions of ultramafic to mafic rocks (almost 1:1), along with chromitite layers. The younger intrusions also occur higher in the stratigraphy of the Karelian Supergroup, and can be floored by either Archean basement rocks or Paleoproterozoic supracrustal rocks (*see* Figures 14.3 and 14.4). Although most abundant in Finland, they also occur in the Kola Peninsula, most notably the Imandra lopolith, which occurs much higher in the Strelna Group than do the older intrusions (*see* Figure 14.3).

An alternative classification of the Fennoscandian mafic intrusions has been proposed by Alapieti (2005a); a three-fold classification based on the abundance of ultramafic material in the intrusions:

1. Ultramafic to mafic type (Tornio, Kemi, Näränkävaara, Kivakka, Monchegorsk, Burakovo)
2. Mafic type (Koillismaa, Koielainen, Akanvaara, Fedorova–Pana Tundra)
3. Megacyclic type (Pentikat, Portimo complex).

Under this classification, both the ultramafic to mafic and mafic types contain intrusions of both ~2500 and ~2440 Ma age. Alapieti (2005a) suggests that the ultramafic to mafic type and the lowermost parts of the megacyclic type crystallized from a boninite-like magma with high MgO and Cr and low TiO_2, whereas the mafic type and upper parts of the megacyclic type crystallized from a more evolved magma.

All Geon 24 mafic intrusions in Fennoscandia are metamorphosed at greenschist or amphibolite facies, and texturally resemble the metamorphosed East Bull Lake intrusions. Much of the reported Ni-Cu-PGE mineralization from the Fennoscandian intrusions occurs in "reef" environments, several types of which have been recognized (Alapieti 2005a). Within the Portimo Complex, however, contact-style mineralization (Iljina 2005), similar to that present in the East Bull Lake intrusive suite is present (Photo 14.1; Table 14.1). It is unclear if the higher proportion of reef-style mineralization present in the

Fennoscandian intrusions represents a fundamentally different type of mineralization environment, or if it is due to the presence of continuous, cored-sections through most intrusions, which more readily enables detection of mineralogical and chemical changes associated with mineralized reefs.

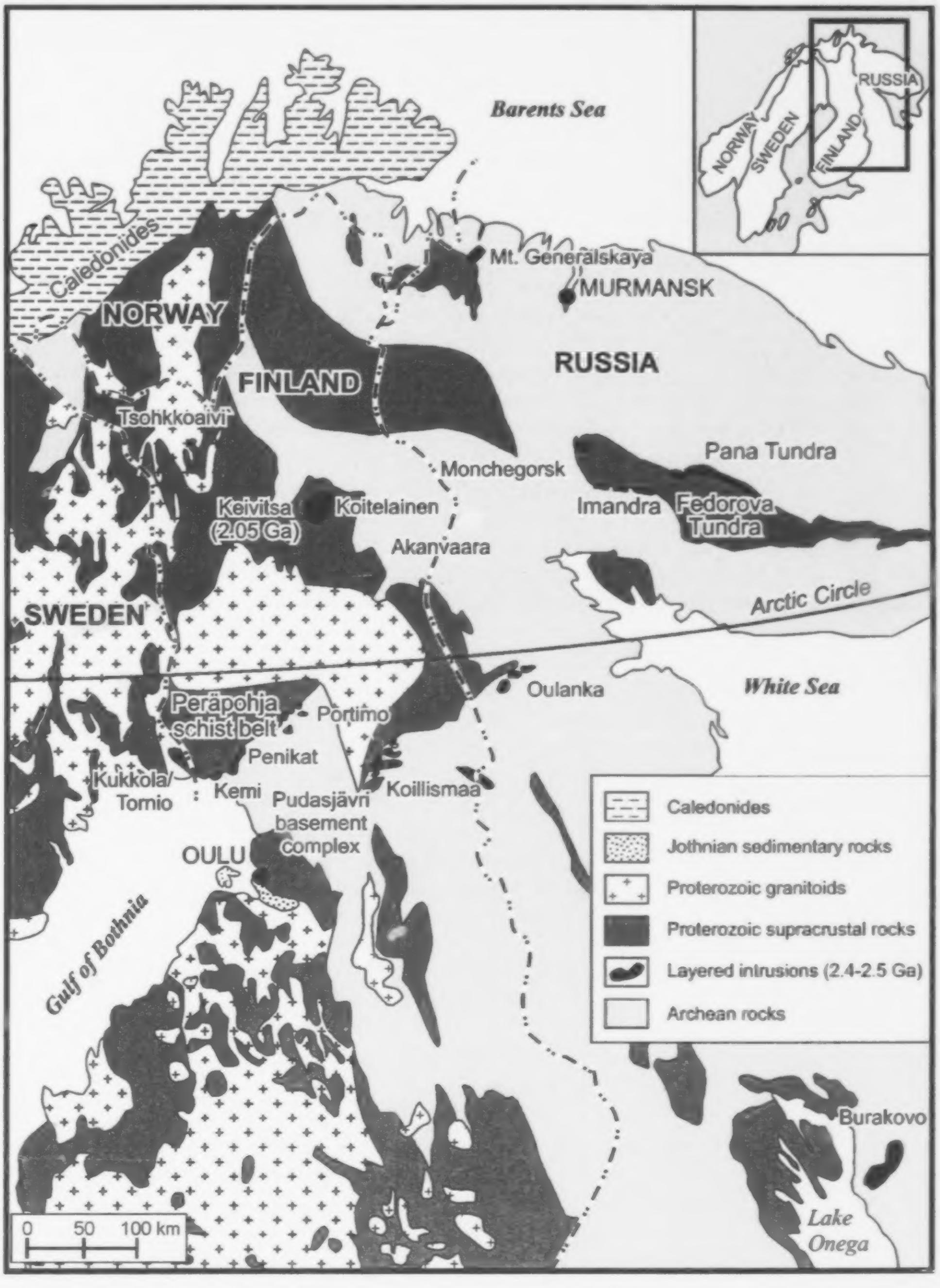

Barents Sea
RUSSIA
NORWAY
SWEDEN
FINLAND
Caledonides
NORWAY
FINLAND
Mt. Generalskaya
MURMANSK
RUSSIA
Tsohkkoaivi
Monchegorsk
Pana Tundra
Keivitsa
(2.05 Ga)
Koitelainen
Imandra
Fedorova
Tundra
Akanvaara
Arctic Circle
SWEDEN
Oulanka
White Sea
Peräpohja
schist belt
Portimo
Penikat
Kukkola/
Tornio
Kemi
Pudasjävri
basement
complex
Koillismaa
OULU
Gulf of Bothnia
Caledonides
Jothnian sedimentary rocks
Proterozoic granitoids
Proterozoic supracrustal rocks
Layered intrusions (2.4-2.5 Ga)
Archean rocks
Burakovo
Lake
Onega
0 50 100 km

Figure 14.4. Simplifed geological map of Fennoscandian showing distribution of Geon 24 mafic intrusions, as well as schist belts and basement complexes discussed in the text. *Modified from* Alapieti et al. (1990).

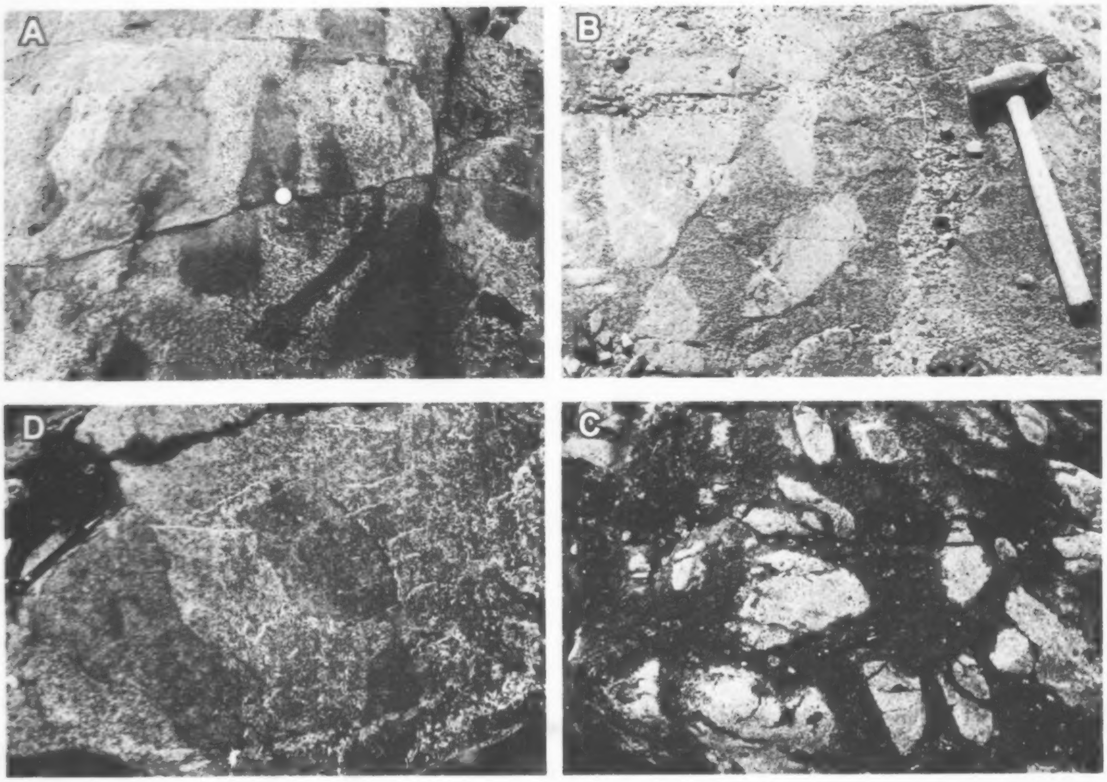


Photo 14.1. Mineralized marginal breccias from the East Bull Lake intrusive suite and Fennoscandian intrusions. **A)** Mafic fragments in medium-grained, leucogabbroic matrix, Dana South area, River Valley intrusion, Ontario. Coin is 2.5 cm in diameter. Photo courtesy of Scott Jobin-Bevans. **B)** Mafic fragments in medium-grained gabbonorite matrix, Agnew Lake intrusion, Ontario. Hammer handle is 35 cm long. Photo courtesy of Scott Jobin-Bevans. **C)** Mafic fragments in medium-grained, leucogabbroic matrix, Konttijärvi intrusion, Portimo Complex, Finland. Note slight scalloping of the fragment margins, similar to that present in Figure 14.4a. Pencil is 14 cm long. Photo by T.R. Hart. **D)** Mafic fragments in medium-grained, gabbronoritic matrix, Konttijärvi intrusion, Portimo Complex, Finland. Red stain on matrix (visible only in *.pdf* version of report) is of biological origin. Pencil is 14 cm long. Photo by T.R. Hart.

Table 14.1. Comparison of estimated copper-platinum group element, contact-style mineralization mineral resources in several mafic intrusions. Note: Lac des Iles is included for comparative purposes, even though it is not a true contact-style deposit. Abbreviations: g = grams, If = inferred, In = indicated, M = measured, t = tonne.

Deposit and/or Intrusion	**Tonnage and resource type**	**Pd g/t**	**Pt g/t**	**Au g/t**	**Cu wt.%**	**Cut-off grade**	**Source**
River Valley Intrusion, Ontario, Dana North and Lismer's Ridge	25.4 million (M, In)	0.98	0.34	0.06	0.10	0.7 g/t Pd and Pt	Pacific North West Capital Corporation, press release, July 22, 2004
Suhanko intrusion, Portimo Complex, Konttijärvi deposit	38.8 million (M, In, If)	1.72	0.48	0.102	0.17	0.5 g/t Pd, Pt and Au	Gold Fields Limited, 2004 Annual Report, Mineral Resource & Reserve
Ahmavaara deposit	60.0 million (M, In, If)	1.40	0.30	0.16	0.27		
Suhanko intrusion, Portimo Complex, Finland, total resource	118.9 million (M, In, If)	1.47	0.35	0.15	0.23	0.5 g/t Pd, Pt and Au	Gold Fields Limited, 2004 Annual Report, Mineral Resource & Reserve
Lac des Iles mine, Thunder Bay, Ontario	145.6 million (M, In)	1.57	0.17	0.12	0.06		North American Palladium Ltd., press release, March 5, 2001

Discussion

GEOCHRONOLOGICAL COMPARISONS

Table 14.2 summarizes the geochronological constraints on the timing of major events within the southern Superior, Wyoming and Karelian cratons between 2500 and 2000 Ma. Several patterns are apparent. First, there are 2 distinct pulses of mafic magmatism in the Superior, Wyoming and Karelia cratons, one at ~2500 to 2475 Ma, the other at ~2450 to 2440 Ma. This observation would appear to strengthen the previously suggested connection between the 3 regions.

On the other hand, the geographic distribution of intrusions resulting from the 2 different magmatic pulses is difficult to interpret. A simplistic interpretation, illustrated in Figure 14.2, is that the older pulse of mafic magmatism, although perhaps less voluminous, was distributed over a larger area. If the magmatism was the result of a mantle plume, it is possible that the magma chambers represented by these intrusions formed either off-axis, or as dike-swarmed spawned chambers (Ernst, Grosfils and Mege 2001). In contrast, the more voluminous, but more geographically centralized distribution of the 2440 to 2450 Ma magmatic pulse, which apparently includes larger volumes of associated felsic magmatism, may owe its origin to magma chambers more centrally located to the plume head.

Table 14.2. Comparison of geological history of rocks from the Superior, Wyoming and Karelian cratons between 2500 and 2000 Ma. All ages are U/Pb ages, unless otherwise noted, and are reported in Ma.

Event	Superior–Sudbury	Wyoming	Karelia
Layered mafic intrusions	Not present	not present	2048–2058 2090 volcanics
Dike swarm 5	2121 and 2101 (Marathon swarm, normal and reversed)	no data or not present	not present
Dike swarm 4	Not present	no data or not present	2148
Dike swarm 3	2172–2167 (Biscotasing swarm)	no data or not present	not present
Mafic magmatism	2220–2210 Ma Nipissing intrusive suite	no data or not present	2203–2222 mafic dikes and gabbro bodies 2250 volcanics
Main Sedimentation	>2220 but <2450	<2475	>2250 but <2450
Felsic plutons	2475 2460–2450 ~2390	2460–2450 + metamorphism	no data?
Dike Swarm 2	~2446	no data or not present	~2440
Volcanism felsic		no data or not present	
mafic	~2450		~2440–2435
Layered mafic intrusions	Not present	not present	2445–2440
Dike Swarm 1	~2475	no data or not present	no data or not present
Layered mafic intrusions	2490–2475	~2477	2502–2491
Early Sedimentation	No data or not present	no data or not present	pre-2500 in Kola area?
Age of basement	2680–2640 (Ramsey–Algoma granitoid complex)		2670–2620 (Pudasjävri basement complex, hosts Kemi and Portimo complex intrusions)

Second, the history of the southern Superior and Karelian cratons may be closely linked, at least until roughly 2200 Ma. The presence of mafic dikes and small gabbro bodies, which are geographically widespread, and ranging in age from 2222 to 2203 in Fennoscandia, may be counterparts to the Nipissing gabbro bodies in Ontario. As some Nipissing gabbro bodies in Ontario are known to host Ni-Cu-PGE mineralization (Jobin-Bevans and Keays 2005; Sproule et al. 2005), similar Ni-Cu-PGE potential may exist in the larger Geon 22 mafic intrusions in Finland.

Third, after 2200 Ma, the geological history of Ontario and Karelia diverge, with Karelia recording mafic diking, intrusive and volcanic events at ~2150 Ma and 2090 to 2050 Ma that are not found in Ontario. Karelia is subjected to a major metamorphic and deformation event at 1880 to 1850 Ma. Although this age range is similar to that of the Penokean orogeny in North America, it is equally possible that this event is related to another segment of the major Paleoproterozoic orogenic belt that girdles North America, and that Karelia and Ontario were not proximal during Geon 18.

BASEMENT COMPARISONS

The Archean Pudasjävri basement complex (*see* Figure 14.4), which hosts the Tornio, Kemi, and Pentikat intrusions, and the Koillismaa and Portimo complexes, consists mainly of granodioritic gneiss and migmatite which give U/Pb ages of 2670 to 2660 Ma (Perttunen and Vaasjoki 2001), and which are cut by granite intrusions of ~2620 Ma age (Perttunen and Vaasjoki 2001). The age and composition of the Pudasjävri basement complex is broadly similar to the age and composition of the Ramsey–Algoma granitoid complex (Prevec 1993) and the host rocks to the River Valley intrusion (Easton 2003), and it is possible that they may be part of the same Archean terrane or subprovince. This is not unexpected, as in Heaman's (1997) reconstruction, the Pudasjävri basement complex is the region of Karelia most proximal to North America. If correct, this linkage would suggest that more attention should be paid to comparing the Tornio, Kemi, and Pentikat intrusions, and the Koillismaa and Portimo complexes with rocks of the East Bull Lake intrusive suite. From this perspective, it may be no coincidence that the best examples of contact-style Ni-Cu-PGE mineralization in Fennoscandia occur at the Konttijärvi deposit in the Suhanko intrusion of the Portimo Complex (Iljina 2005), at the Ahmavaara deposit in the Portimo Complex (Iljina 2005), and in parts of the western Koillismaa complex (Alapieti 2005b)(*see* Figure 14.4). Perhaps emplacement of Geon 24 mafic magmas into relatively young, felsic, Archean crust is a factor in the development of contact-style mineralization.

Basement correlation between Fennoscandia and North America becomes more problematic as one moves west in Fennoscandia, likely because of the presence of Archean terranes or subprovinces that have no direct counterparts with those present in the Superior Province.

CORRELATION OF OVERLYING SUPRACRUSTAL ROCKS

If there are similarities between the Archean basement rocks and the Geon 24 mafic intrusions between North America and Fennoscandia, are there also rocks correlative with the Huronian Supergroup in Fennoscandia? Again, comparisons are most easily examined in western Finland, due to its likely proximity to North America during Geon 24 to Geon 22. Supracrustal rocks comprising the Peräpohja schist belt of western Finland (*see* Figure 14.4) are divided into 2 groups, the older Kivalo Group and the younger Paakkola Group (Hanski 2001). Metavolcanic rocks from within the Paakkola Group yield a Nd/Sm isochron age of 2090±70 Ma (Huhma et al. 1990), clearly indicating that the Paakkola Group is unlikely to have any equivalents in the southern Superior Province.

In the case of the Kivalo Group, metaconglomerate, overlain by mafic volcanic rocks of the Runkaus Formation, unconformably overlie leucogabbroic rocks of the Kemi intrusion (Alapieti and Huhtelin 2005), indicating that the mafic intrusion was exposed and eroded prior to sedimentation. Although such a relationship is inferred to be present in the Southern Province, it has yet to be clearly demonstrated (e.g., James et al. 2002). Metavolcanic rocks from the Runkaus Formation yield a Nd/Sm isochron age of 2330±80 Ma (Huhma et al. 1990), consistent with the aforementioned unconformity and with the fact that the Kivalo Group is cut by ~2200 Ma mafic dikes. This age range is similar to that of the Huronian Supergroup. Detailed correlation between the Kivalo Group and the Huronian Supergroup is problematic, however. For example, one could argue that the Sompujärvi, Runkaus, Palokivalo and Jouttiaapa formations are equivalents to the Elliot Lake Group, with conglomerate and arenite units representing the Matinenda Formation, and mafic metavolcanic units representing the Elsie Mountain and Stobie formations. Unfortunately, the overlying carbonate and quartzite units of the Poikkimaa, Hirsimaa and Rantamaa formations are most similar to the uppermost units of the Marquette Range Supergroup in Michigan, which would mean that much of the exposed Huronian Supergroup in Ontario (Hough Lake, Quirke Lake, and lowermost Cobalt groups) would be absent from the section in the Peräpohja schist belt, assuming the correlation of metavolcanic units is correct. Although difficult, correlation of the supracrustal rocks present in the Huronian Supergroup, the Marquette Range Supergroup and the Peräpohja schist belt might prove useful in helping to unravel the depositional and tectonic history of southern Superior–Karelia during Geon 24 to Geon 22.

Implications for Exploration

The geological comparisons described above between North America and Fennoscandia have several implications with respect to exploration.

1. Mafic intrusions associated with the ~2450 to 2440 Ma magmatic event are not only more voluminous in Finland, but host most of the Cu-Ni-PGE deposits. This younger suite also contains Cr-rich intrusions not present in the older suite.

2. If current tectonic re-constructions are valid (*see* Figure 14.2), then the likelihood of finding intrusions of the younger suite in either the Wyoming or Superior cratons is limited. If they do occur in the Superior craton, then they may be buried beneath Huronian Supergroup rocks south of the Murray fault, or are beneath the allochthonous thrust sheets of the northern Grenville Province.

3. Rocks of Geon 22 age in Finland may be analogous to the Nipissing intrusive suite and, consequently, may host similar Ni-Cu-PGE mineralization.

4. It is possible that the southern Superior and Karelia cratons may have been linked between 2680 to 2200 Ma. After 2200 Ma, the geological histories of Karelia and southern Superior diverge significantly.

5. Contact-style Ni-Cu-PGE mineralization in both in the southern Superior craton and in western Finland is hosted in mafic intrusions emplaced into relatively young (Geon 26), felsic, Archean crust.

6. A two-stage rifting process, which generates a configuration of broader, older flanks and centralized, younger cores, may apply to other plume systems at several scales, such as the Lake Nipigon region of the Midcontinent rift in the Superior craton (e.g., Easton 2005).

Several observations were made by the authors with respect to exploration for PGE±Ni-Cu reefs in the Finnish Geon 24 mafic intrusions that may be relevant to exploration in the East Bull Lake intrusive suite. First, the reefs are broad zones of mineralization (generally several metres thick rather than centimetre-thick zones. Second, the reefs may or may not be associated with sulphide, however, the non-sulphide reefs were all found by examining adjacent rock units containing sulphide (Halkoaho, Alapieti and Huhtelin 2005). The reefs occur where magma composition changes, and may involve erosion of underlying cumulate rocks, including the formation of potholes (i.e., dynamic magma system, new magma pulse) (Halkoaho, Alapieti and Huhtelin 2005). There is also an association with poikilitic anorthosite, also referred to by the field terms "spotted" or "mottled" anorthosite (Halkoaho, Alapieti and Huhtelin 2005). These rocks can serve either as a caprock to a mineralized unit, or as unit in which PGE-rich intracumulus fluids can accumulate.

Applying these observations to the East Bull Lake intrusive suite yields 4 potential targets. In the East Bull Lake intrusion, the first target is the olivine gabbronorite zone, just below the overlying plagioclase-rich rocks. James et al. (2002) also suggested this as a potential reef setting. The second is the base of the dendrite zone, assuming that the dendrites represent fluid escape channels above a reef. In the River Valley intrusion, south of the Sturgeon River, is an oxide-bearing leucogabbro unit, which is closely associated with clotty-textured anorthosite, which may represent a higher metamorphic grade version of poikilitic anorthosite. This horizon was suggested as a potential reef environment by Easton (2003). North of the Sturgeon River, closer attention should be paid to the areas where true anorthosite is present in the intrusion. These occur near the exposed stratigraphic top of the intrusion north of the Sturgeon River, and it is possible that much of any reef horizon may have been eroded away.

PART 2. UNDERLYING CONTROLS ON PGE MINERALIZATION

The contact-style mineralization of a number of the Fennoscandian intrusions may be the result of extensive and prolonged interaction of the intrusion with country rock (Iljina and Lee 2005). The composition of the country rocks is of significance in this style of mineralization, and Mungall (2005) presented the results of modelling of assimilation of different compositions. Assimilation of a sulphur-rich sediment will result in a greater volume of sulphide, commonly forming larger tonnage base metal mineralization with lower PGE grades. In contrast, assimilation of sediment lacking sulphur will result in sulphide saturation of the magma at a lower sulphur concentration, with resultant possible formation of low tonnage, but high-grade PGE mineralization. The results of Mungall's (2005) modelling may explain the presence of PGE mineralization in some Geon 24 mafic magmas, and also the Geon 11 ultramafic intrusions of the Lake Nipigon area, both of which intrude felsic Archean crust that lacks any obvious sulphur-rich country rock.

The composition of the parental magma in either the contact- or reef-style of PGE mineralization is important in understanding the formation of the mineralization and the tectonic history of the intrusion. Alapieti (2005a) suggested that the magmas forming the lowermost parts of the megacyclic type and the ultramafic to mafic type intrusions crystallized from a boninite-like parental magma with high MgO and Cr and low TiO_2. A boninite is formed by more than 30% partial melting, at relatively low pressure and temperature, of a fertile mantle harzburgite that has undergone previous significant partial melting in the shallowest parts of subduction zones, or the forearc area (e.g., Mungall 2005). However, both the Fennoscandian Geon 24 mafic intrusions, and the East Bull Lake intrusive suite, are interpreted to have formed in a plume system (e.g., Easton 2005). Another possibility is that these magmas formed as a result of a komatiitic magma that assimilated more than half of its own weight in crustal material while crystallizing a similar mass of ultramafic cumulates (e.g., Mungall 2005). Distinguishing between the products of these 2 different processes is difficult, as either model would produce magmas of very similar composition.

Assimilation of country rocks may not have occurred at the current site of the mineralization, but rather at some mid-crustal level where the magma rose to higher crustal levels through a series of magma conduits (e.g., Arndt 2005). Formation of phases that concentrate the PGE (e.g., sulphides or chromite) may also occur at mid-crustal levels. These phases may then either be entrained and transported by the magma or deposited and subsequently re-worked with final deposition at the current site of mineralization (e.g., Arndt 2005; Mungall 2005). In these dynamic systems, the physical form of the magma conduit becomes significant, as features such as embayments and transitions from restricted conduits to larger sills or dikes effect the transport of entrained phases and interaction with the wall rocks or previously deposited mineralization (e.g., Arndt 2005). Portions of these conduit systems may be indicated by excessive amounts of cumulate phases and a lack of mafic or felsic fractionates (e.g., Mungall 2005), and may explain the occurrence of PGE mineralization in the Seagull intrusion of the Lake Nipigon area (e.g., Hart 2005). Formation of the initial mineralization at deeper levels has been suggested for mineralization at Lac des Iles (Hinchey, Hattori and Lavigne 2005) and for a number of deposits including Bushveld and Voisey's Bay (e.g., Kruger 2005; Arndt 2005).

Much of the reported Ni-Cu-PGE mineralization from the Fennoscandian Geon 24 mafic intrusions occurs in reef-style environments (Alapieti 2005a). Cawthorn (2005) discusses the complications of exploring in reef-type environments in the relatively well-known Bushveld Intrusion, where the Rustenburg facies reef is considered to be the type section for the intrusion, mainly because mining first began in the Rustenburg area. Cawthorn (2005) describes how the vertical lithologic succession and position of PGE mineralization varies on both a small and regional scale along strike with this section. The high degree of variation that is described by Cawthorn (2005) suggests that tracing PGE mineralization, or stratigraphy, in the initial stages of an exploration program could be difficult. The presence of pothole structures adds an additional complexity, with a pothole in the Union and Northam Platinum mines descending over 20 m into the footwall at a high angle to the layering and extending for over 20 km along strike. Besides the difference in the volume of exploration data available for the Fennoscandian Geon 24 mafic intrusions versus those in Ontario, complexities of the type described by Cawthorn (2005) may also explain the apparent lack of reef-style mineralization in the Ontario Geon 24 mafic intrusions.

Barnes et al. (1993) proposed that one means of identifying reef-style mineralization is based on an increase in Cu/Pd ratios, resulting from PGE depletion and identifying that the magma has equilibrated with sulphide liquid. Cawthorn (2005) cautions there is no corresponding increase in the Cu/Pd ratio associated with the UG2 reef in the Bushveld Intrusion, but that there is an increase in the ratio associated with the Merensky Reef of the Bushveld Intrusion. Mungall (2005) suggested that the identification of magmas that have only been slightly depleted in PGE, versus strongly depleted magmas, when compared to their initial compositions, may be a key to identifying those magmas associated with PGE-rich mineralization. Unfortunately, identification of material that may provide an indication of the initial magmatic PGE concentrations can be problematic. Chill phases of intrusions commonly are considered to be a close approximation of initial magma composition, but some chilled phases are contaminated as a result of assimilation. The Cu/Pd ratio, however, has been demonstrated to be a useful tool in a variety of PGE mineralized environments (Maier and Barnes 2005).

REFERENCES

Alapieti, T.T. 2005a. Classification of the Fennoscandian early Palaeoproterozoic (2.5–2.4 Ga) layered intrusions and related PGE deposits; Extended Abstracts, 10th International Platinum Symposium, August 8–11, 2005, Oulu, Finland, p.21-24.

——— 2005b. Koillismaa layered complex and related copper-nickel and PGE mineralization; *in* Early Palaeoproterozoic (2.5–2.4) Tornio–Näränkävaara layered intrusion belt and related chrome and platinum-group element mineralization, northern Finland, Geological Survey of Finland, Guide 51a, p.101-110.

Alapieti, T.T., Filen, B.A., Lahtinen, J.J., Lavrov, M.M., Smolkin, V.F., and Voitsekhovsky, S.N. 1990. Early Proterozoic layered intrusions in the northeastern part of the Fennoscandian Shield; Mineralogy and Petrology, v.42, p.1-22.

Alapieti, T.T. and Huhtelin, T.A. 2005. The Kemi intrusion and associated chromitite deposit; *in* Early Palaeoproterozoic (2.5–2.4) Tornio–Näränkävaara layered intrusion belt and related chrome and platinum-group element mineralization, northern Finland, Geological Survey of Finland, Guide 51a, p.13-32.

Amelin, Y.V., Heaman, L.M. and Semenov, V.S. 1995. U-Pb geochronology of layered mafic intrusions in the eastern Baltic Shield: implications for the timing and duration of Paleoproterozoic continental rifting; Precambrian Research, v.75, p.31-46.

Arndt, N.T. 2005. The conduits of magmatic ore deposits; *in* Exploration for platinum-group element deposits, Mineralogical Association of Canada, Short Course Volume 35, p.181-198.

Barnes, S.J., Couture, J.-F., Sawyer, E.W. and Bouchaib, C. 1993. Nickel-copper occurrences in the Belleterre–Angliers Belt of the Pontiac Subprovince and the use of Cu-Pd ratios in interpreting platinum group element distributions; Economic Geology, v.88, p.1402-1418.

Cawthorn, R.G. 2005. Stratiform platinum-group element deposits in layered intrusions; *in* Exploration for platinum-group element deposits, Mineralogical Association of Canada, Short Course Volume 35, p.57-74.

Chen,Y.D., Krogh, T.E. and Lumbers, S.B. 1995. Neoarchean trondhjemitic and tonalitic orthogneiss identified within the northern Grenville Province in Ontario by precise U-Pb dating and petrologic studies; Precambrian Research, v.72, p.263-281.

Corfu, F. and Easton, R.M. 2000. U-Pb evidence for polymetamorphic history of Huronian rocks underlying the Grenville Front Tectonic Zone east of Sudbury, Ontario; Chemical Geology, v.172, p.149-171.

Easton, R.M. 1999. PGE, Ni, Cu, and Cr potential of mafic rocks within the Grenville Front tectonic zone east of Sudbury; *in* Ontario Geological Survey, Miscellaneous Paper 169, p.195-202.

——— 2000. Variation in crustal level and large scale tectonic controls on rare-metal and platinum-group element mineralization in the Southern and Grenville provinces; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p.28-1 to 28-16.

——— 2003. Geology and mineral potential of the Paleoproterozoic River Valley Intrusion and related rocks, Grenville Province; Ontario Geological Survey, Open File Report 6123, 171p.

——— 2005. The Midcontinent Rift in Ontario: a short, but complicated tale of crustal sagging, softening and splitting?; Geological Society of America, Abstracts with Programs, v.36, no.5, p.73.

Easton, R.M., Jobin-Bevans, S.L. and James, R.S. 2004. Geological guidebook to the Paleoproterozoic East Bull Lake intrusive suite plutons at East Bull Lake, Agnew Lake and River Valley, Ontario; Ontario Geological Survey, Open File Report 6135, 84p.

Ernst, R.E., Grosfils, E.B. and Mege, D. 2001. Giant dike swarms: Earth, Venus and Mars; Annual Reviews of Earth and Planetary Science, v.29, p.489-534.

Halkoaho, T., Alapieti, T. and Huhtelin, T. 2005. The Sompujarvi, Ala-Penikka and Paasivaara PGE reefs in the Pentikat layered intrusion, northern Finland; *in* Early Palaeoproterozoic (2.5–2.4) Tornio–Näränkävaara layered intrusion belt and related chrome and platinum-group element mineralization, northern Finland, Geological Survey of Finland, Guide 51a, p.33-76.

Hanski, E. 2001. History of stratigraphical research in northern Finland; *in* Radiometric age determinations from Finnish Lapland and their bearing on the timing of Precambrian volcano-sedimentary sequences, Geological Survey of Finland, Special Paper 33, p.15-43.

Hart, T.R. 2005. Precambrian geology of the southern Black Sturgeon River and Seagull Lake map area, Nipigon Embayment, northwestern Ontario; Ontario Geological Survey, Open File Report 6165, 63p.

Heaman, L.M. 1997. Global magmatism at 2.45 Ga: Remnants of an ancient large igneous province?; Geology v.25, p. 299-302.

Hinchey, J.G., Hattori, K.H. and Lavigne, M.J. 2005. Geology, petrology, and controls on PGE mineralization of the southern Roby and Twilight Zones, Lac des Iles Mine, Canada; Economic Geology, v.100, p.43-61.

Huhma, H., Cliff, R.A., Perttunen, V. and Sakko, M. 1990. Sm-Nd and Pb isotopic study of mafic rocks associated with early Paleoproterozoic continental rifting: the Peräpohja schist belt in northern Finland; Contributions to Mineralogy and Petrology, v.104, p.369-379.

Iljina, M. 2005. Portimo layered igneous complex; *in* Early Palaeoproterozoic (2.5–2.4) Tornio–Näränkävaara layered intrusion belt and related chrome and platinum-group element mineralization, northern Finland, Geological Survey of Finland, Guide 51a, p.77-100.

Iljina, M., Heikura, P. and Salmirinne, H. 2005. The Haukiaho and Kaukua PGE-Cu-Ni-Au prospects in the Koillismaa Layered Igneous Complex, Finland; Geological Survey of Finland, Report CM06/3543,3544/2005/1/10, http://www.gtk.fi/explor/kaukua/haukiaho_kaukua.pdf (12.1 MB) [accessed 11 October 2005].

Iljina, M.J. and Lee, C.A. 2005. PGE deposits in the marginal series of layered intrusions; *in* Exploration for platinum-group element deposits, Mineralogical Association of Canada, Short Course Volume 35, p.75-96.

James, R.S., Easton, R.M., Peck, D.C. and Hrominchuk, J.L. 2002. The East Bull Lake intrusive suite: remnants of a ~2.48 Ga large igneous and metallogenic province in the Sudbury area of the Canadian Shield; Economic Geology, v.97, p.1577-1606.

Jobin-Bevans, L.S. and Keays, R.R. 2005. Geochemistry of the River Valley intrusion and the Nipissing gabbro suite, Sudbury, Ontario: implications for ore forming processes; Extended Abstracts, 10th International Platinum Symposium, August 8–11, 2005, Oulu, Finland, p.133-136.

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U-Pb zircon and baddelyite ages for the Sudbury Structure; Ontario Geological Survey, Special Volume 1, p.431-446.

Kruger, F.J. 2005. The main zone of the Bushveld Complex: source of the Merensky Reef and Platreef; Extended Abstracts, 10th International Platinum Symposium, August 8–11, 2005, Oulu, Finland, p.157-159.

Maier, W.D. and Barnes, S.J. 2005. Application of lithogeochemistry to exploration for PGE Deposits; *in* Exploration for platinum-group element deposits, Mineralogical Association of Canada, Short Course Volume 35, p.309-342.

Mungall, J.E. 2005. Magmatic geochemistry of the platinum-group elements; *in* Exploration for platinum-group element deposits, Mineralogical Association of Canada, Short Course Volume 35, p.1-34.

Perttunen, V. and Vaasjoki, M. 2001. U-Pb geochronology of the Peräpohja schist belt, northwestern Finland; *in* Geological Survey of Finland, Special Paper 33, p.45-84.

Prevec, S.A. 1993. An isotopic, geochemical and petrographic investigation of the genesis of early Proterozoic mafic intrusions and associated volcanics near Sudbury, Ontario; unpublished PhD thesis, University of Alberta, Edmonton, Alberta, 223p.

Sproule, R.A., Lesher, C.M., Sutcliffe, R. and Tracanelli, H. 2005. Nipissing-aged Ni-Cu-PGE mineralization in the Shakespeare intrusion; Extended Abstracts, 10th International Platinum Symposium, August 8–11, 2005, Oulu, Finland, p.239-242.

Vogel, D.C., Vuollo, J.I., Alapieti, T.T. and James, R.S. 1998. Tectonic, stratigraphic, and geochemical comparisons between ca. 2600–2440 Ma mafic igeneous events in the Canadian and Fennoscandian shields; Precambrian Research, v.92, p.89-116.

Wodicka, N. and Card, K.D. 1995. Late Archean history of the Levack gneiss complex, southern Superior Province, Sudbury, Ontario: New evidence from U-Pb geochronology; Precambrian '95, Program with Abstracts, p.191.

15. Project Unit 04-013. Timing of Gold Mineralization in the Western Grimsthorpe Domain, Central Metasedimentary Belt, Grenville Province

R.M. Easton[1] and S.L. Kamo[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Jack Satterly Geochronology Laboratory, Department of Earth Sciences, University of Toronto, Toronto, Ontario

INTRODUCTION

As reported in Easton (2004), approximately 6 weeks of the 2004 field season were devoted to geological mapping and sampling in western Tudor and eastern Grimsthorpe townships, in order to better understand the controls on gold mineralization in those townships. This work was undertaken because of active gold exploration in the area that has been taking place since 1989. As part of that study, 3 samples were collected for U/Pb geochronology in order to bracket the timing of gold mineralization in the area, as well as to provide additional timing constraints on the geological history of the Grimsthorpe domain. This paper presents the results of this geochronological study.

WESTERN GRIMSTHORPE DOMAIN

Geology

The map area straddles 2 geological domains of the Central Metasedimentary Belt: Belmont and Grimsthorpe, with the study focussing on Grimsthorpe domain (Figure 15.1). The Belmont domain consists of several discrete packages of bimodal metavolcanic rocks, ranging in age from 1287 to 1250 Ma, as well as siliciclastic and carbonate metasedimentary rocks, all of which are intruded by mafic (Lavant intrusive suite) and granitic (Methuen intrusive suite) plutons at circa 1245 Ma (Easton 1992). Metamorphic grade in the Belmont domain, particularly the southern and eastern parts of the domain ranges from middle greenschist to lower amphibolite facies. Adjacent to the study area, the Belmont domain consists mainly of grey, thin bedded, calcite marbles with interbedded metasiltstone and locally metasandstone. In contrast, the Grimsthorpe domain is dominated by mafic, metavolcanic and volcaniclastic metasedimentary rocks that are older than 1270 Ma. Carbonate metasedimentary rocks are rare. Plutonic rocks are dominated by tonalite and granodiorite plutons of the Elzevir intrusive suite. Metamorphic grade ranges from lower to middle greenschist facies in the south and east, to amphibolite facies in the north (Easton 1992).

Two major supracrustal packages occur within the Grimsthorpe domain (Easton 1992; Easton and Ford 1994), as follows, from youngest to oldest:

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.15-1 to 15-10.

© Queen's Printer for Ontario, 2005

- *Grimsthorpe Group:* Metasedimentary rocks derived from a mafic volcanic and gabbroic source region, minor metabasalt flows. Main rock types are matrix- and clast-supported metaconglomerate, gabbro cobble metaconglomerate, meta-arenite, metawacke, minor metasiltstone, metapelite, rusty schist. Minor pillowed and massive tholeiitic metabasalt flows.

unconformity?

- *Canniff Complex:* Massive and pillowed tholeiitic metabasalts, spilitic metabasalts; protomylonitic metagabbro and metaperidotite. Ultramafic rocks commonly altered to talc ± anthophyllite ± actinolite rocks.

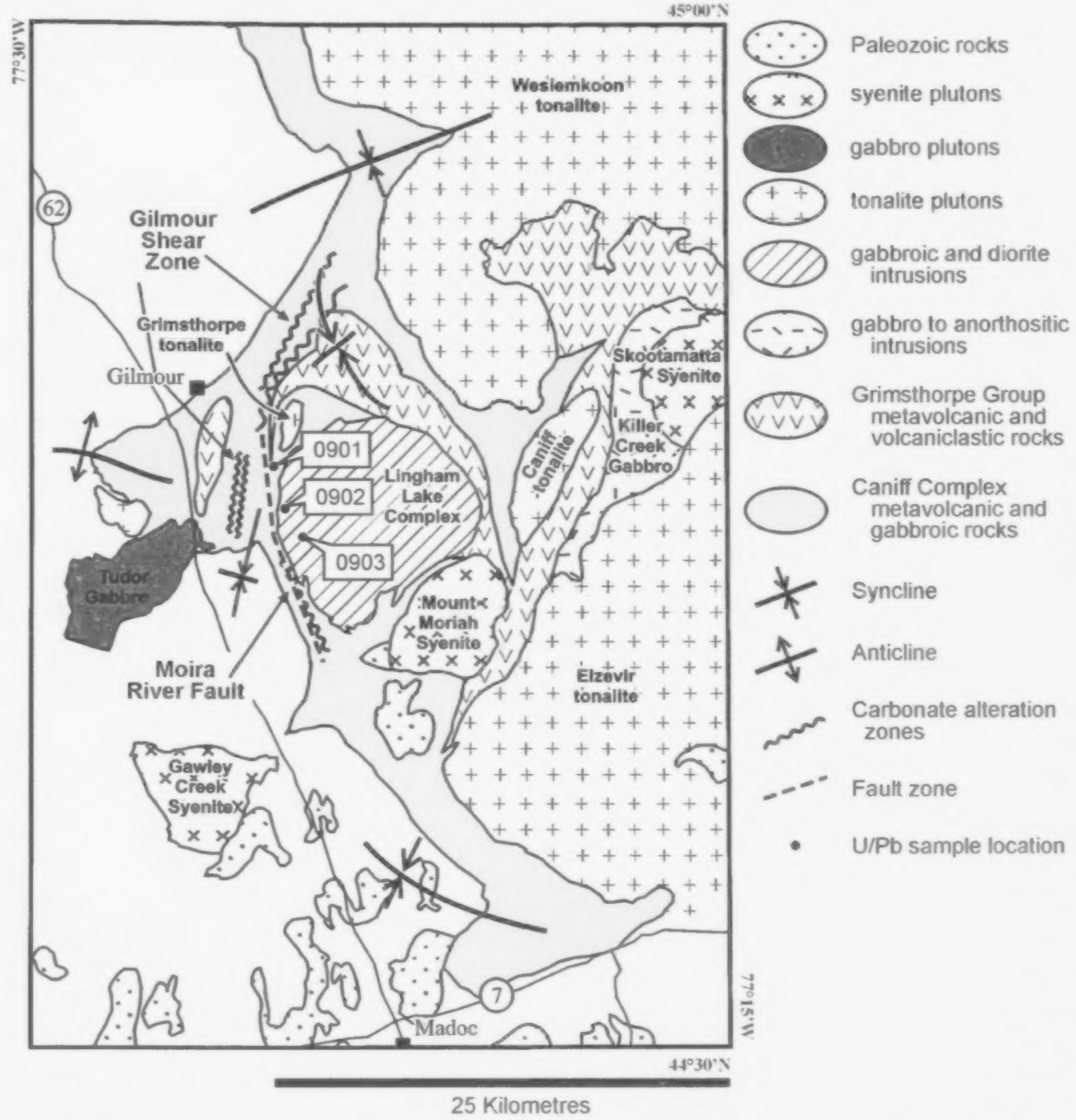

45°00'N
77°30'W
77°15'W
44°30'N
Weslemkoon tonalite
62
Gilmour Shear Zone
Grimsthorpe tonalite
Gilmour
0901
0902
0903
Lingham Lake Complex
Canniff tonalite
Skootamatta Syenite
Killer Creek Gabbro
Tudor Gabbro
Mount Moriah Syenite
Moira River Fault
Elzevir tonalite
Gawley Creek Syenite
7
Madoc
25 Kilometres
Paleozoic rocks
syenite plutons
gabbro plutons
tonalite plutons
gabbroic and diorite intrusions
gabbro to anorthositic intrusions
Grimsthorpe Group metavolcanic and volcaniclastic rocks
Caniff Complex metavolcanic and gabbroic rocks
Syncline
Anticline
Carbonate alteration zones
Fault zone
U/Pb sample location

Figure 15.1. Geological sketch map of the western Grimsthorpe map area, showing major geological features. Only units from the Grimsthorpe domain are shown in detail; rocks of the Belmont domain are not ornamented. U/Pb sample numbers are abbreviated, with only the last 4 digits of the sample numbers shown, for example, 0901 is sample 04RME-0901.

- *Grimsthorpe Group:* Metasedimentary rocks derived from a mafic volcanic and gabbroic source region, minor metabasalt flows. Main rock types are matrix- and clast-supported metaconglomerate, gabbro cobble metaconglomerate, meta-arenite, metawacke, minor metasiltstone, metapelite, rusty schist. Minor pillowed and massive tholeiitic metabasalt flows.

unconformity?

- *Canniff Complex:* Massive and pillowed tholeiitic metabasalts, spilitic metabasalts; protomylonitic metagabbro and metaperidotite. Ultramafic rocks commonly altered to talc ± anthophyllite ± actinolite rocks.

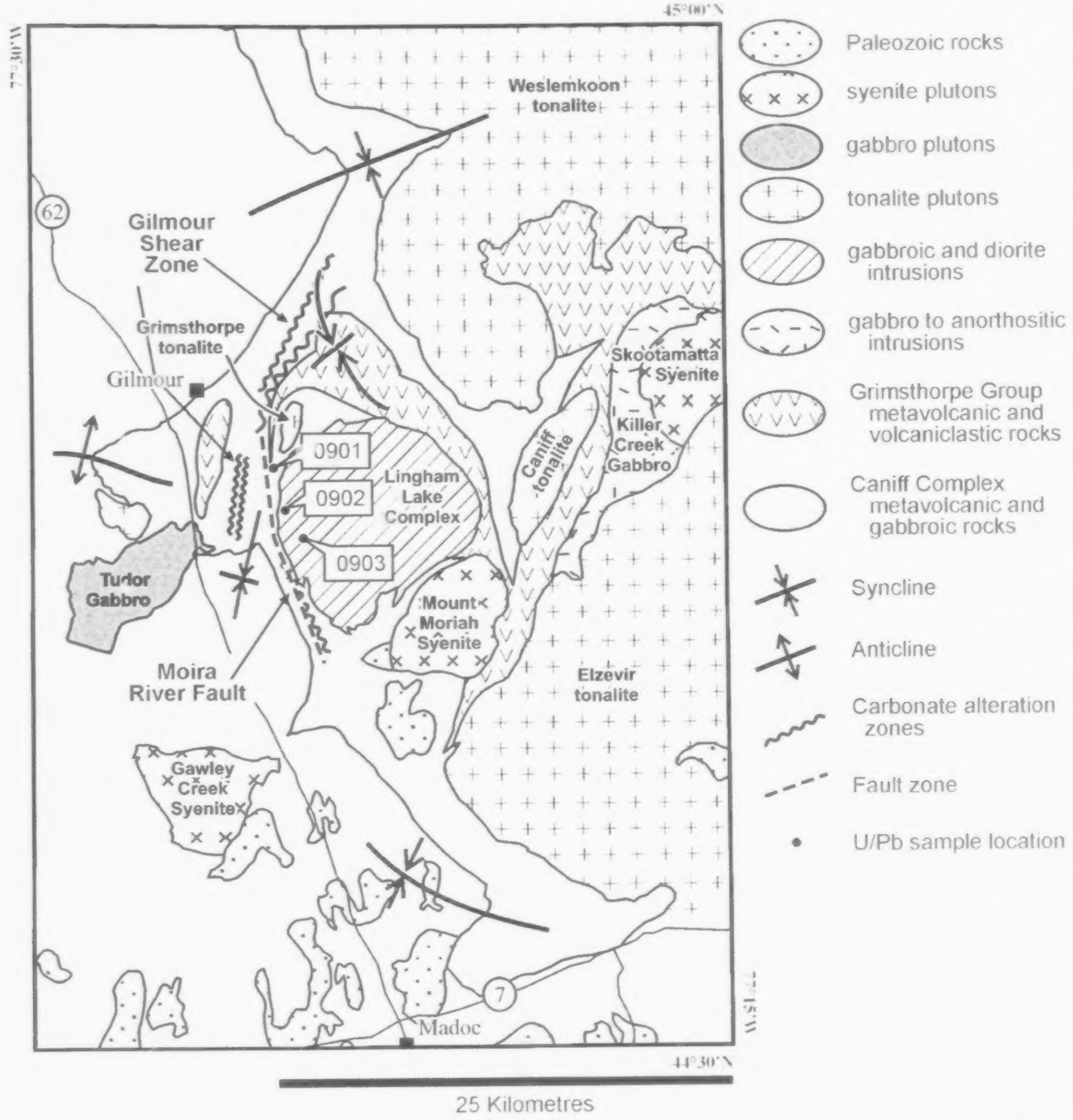

45°00'N
77°30'W
77°15'W
44°30'N
Weslemkoon tonalite
62
Gilmour Shear Zone
Grimsthorpe tonalite
Gilmour
0901
0902
0903
Lingham Lake Complex
Tudor Gabbro
Moira River Fault
Skootamatta Syenite
Killer Creek Gabbro
Caniff tonalite
Mount Moriah Syenite
Elzevir tonalite
Gawley Creek Syenite
7
Madoc
Paleozoic rocks
syenite plutons
gabbro plutons
tonalite plutons
gabbroic and diorite intrusions
gabbro to anorthositic intrusions
Grimsthorpe Group metavolcanic and volcaniclastic rocks
Caniff Complex metavolcanic and gabbroic rocks
Syncline
Anticline
Carbonate alteration zones
Fault zone
U/Pb sample location
25 Kilometres

Figure 15.1 Geological sketch map of the western Grimsthorpe map area, showing major geological features. Only units from the Grimsthorpe domain are shown in detail; rocks of the Belmont domain are not ornamented. U/Pb sample numbers are abbreviated, with only the last 4 digits of the sample numbers shown, for example, 0901 is sample 04RMF-0901.

A U/Pb zircon age of 1279±3 Ma (Heaman et al. 1987) from a felsite within the Grimsthorpe Group in Tudor Township provides a minimum age of deposition for both the Canniff Complex and the Grimsthorpe Group. Both the Grimsthorpe Group and the Canniff Complex are intruded by a variety of younger plutonic rocks (*see* Figure 15.1). These include

1. ultramafic, gabbroic and anorthositic rocks of the Killer Creek intrusive suite (>1270 Ma, Easton 1992)
2. gabbroic and dioritic rocks of the Lingham Lake intrusive complex
3. tonalitic and granodioritic rocks of the Elzevir intrusive suite, emplaced at ~1270 Ma (Heaman et al. 1987). These include the Grimsthorpe, Canniff, Weslemkoon and Elzevir intrusions
4. gabbroic rocks of the Lavant intrusive suite, which were emplaced at ~1240 to 1250 Ma (Easton 1992). The Tudor gabbro is the largest body of this suite in the study area
5. syenitic rocks of the Kensington–Skootamatta suite, which were emplaced at ~1075 to 1090 Ma (Easton 1992). Both the Mount Moriah syenite and the Skootamatta syenite intruded supracrustal rocks of Grimsthorpe domain

There are several notable differences between the eastern and western Grimsthorpe domains. The Grimsthorpe Group in the west contains a higher proportion of metavolcanic rocks (Tudor Formation) than in the east, and mafic rocks of both the Canniff Complex and the Grimsthorpe Group in the western Grimsthorpe domain are more extensively altered than they are in the east. In addition, primary volcanic and sedimentary textures are less commonly observed in supracrustal rocks in the western Grimsthorpe domain. There may also be more felsite horizons in the western Grimsthorpe domain. It remains to be determined if these felsites are felsic flows or tuffs intercalated with the mafic volcanic rocks or if they are simply fine-grained, deformed, intrusive rocks. The Canniff Complex in the western Grimsthorpe domain is dominated by metabasaltic rocks, with a minimal amount of metagabbroic or metaperidotitic rocks.

Alteration

Alteration of the mafic metavolcanic rocks of both the Grimsthorpe Group and the Canniff Complex ranges from minor to intense, and is complex. The dominant form of alteration is the introduction of calcite and dolomite, brown to red-brown weathering ankerite, and quartz into the metavolcanic rocks. This occurs in a variety of forms (*see* Easton 2004 for details):

- Along thin (1 to 10 mm wide) carbonate ± quartz veins injected along fractures. Vein spacing may be on the order of tens of centimetres, but typically is on the order of 1 or 2 cm. Veins may be continuous or discontinuous along strike.
- A more pervasive introduction of carbonate, generally accompanied by the development of chlorite, white mica and/or biotite along cleavage surfaces. Rocks become highly schistose, and weathered surfaces may appear pocked, due to recessive weathering of large carbonate grains.
- An almost complete replacement by red-brown carbonate, producing a fairly massive rock that no longer resembles an igneous rock. Associated with these zones are biotite-rich (>15%) horizons. Quartz veins and pods, typically disrupted, are commonly associated with these zones of intense alteration.

The zones of alteration and extensive quartz veining are anastomosing, particularly in the north. On a property scale, this makes it difficult to trace some of the more intense alteration and mineralized zones along strike. As noted by Christie (1990), at least 2 main fabrics are present in the alteration zones, an early, steep fabric with associated quartz veins and azimuths of 250 to 220°, and a younger, steep, fabric oriented 170 to 180° and closely associated with carbonate flooding. The alteration and vein systems resemble lode gold-bearing systems found in Archean greenstone belts, and exploration techniques developed for Archean systems may be applicable to gold exploration in the Grimsthorpe area.

Alteration of felsite bodies hosting gold mineralization is somewhat different in character to the alteration of the mafic rocks (*see* Easton 2004 for details), in that carbonate alteration is minimal. Instead, alteration consists of disseminated arsenopyrite associated with friable, schistose and chloritic zones in the felsite, as well as zones of discrete, concordant to semi-concordant quartz veins with associated arsenopyrite. Mineralization is associated with the development of a protomylonitic fabric in the felsite.

Shear Zones

Alteration, deformation, quartz veining and mineralization are concentrated along 2 major shear zones in the map area (Easton 2004). These are the older, 250 to 220° trending, Gilmour shear zone (*see* Figure 15.1) and the 170 to 180° trending Moira River shear zone (*see* Figure 15.1). The Gilmour shear zone appears to be truncated at the Belmont–Grimsthorpe domain boundary, as there is no evidence of deformation or alteration of the low-grade Belmont domain marbles directly on strike with the trace of the shear zone. This suggests that the alteration and veining within the Gilmour shear zone occurred before development of the domain boundary (Easton 2004). An alteration zone east of the Moira River, that is part of the Moira River shear zone, is truncated in places by porphyritic monzodiorite of the Lingham Lake intrusive complex, and locally includes inclusion-breccias containing carbonate-altered metavolcanic fragments. This suggests that alteration and veining was largely complete by the time of intrusion of the Lingham Lake intrusive complex, although it is possible that some reactivation of the Moira River shear zone occurred after emplacement of the Lingham Lake intrusive complex.

CENTRAL METASEDIMENTARY BELT GOLD DEPOSITS

Previous attempts to classify gold deposits in the Central Metasedimentary Belt of the Grenville Province of Ontario (e.g., Carter and Colvine 1985; Easton and Fyon 1992; Sangster and Bourne 1982; Sangster, Gauthier and Gower 1992) have focussed on vein mineralogy and/or host-rock associations, rather than attempting to classify them according to gold deposit models related to modern tectonic settings. Furthermore, there has been a tendency to view the Ontario gold deposits as the product of a single event at a single time or time period. Consequently, the gold potential of the Central Metasedimentary Belt is probably underestimated, with past exploration not necessarily focussed on the areas of highest potential.

Table 15.1 is revised classification of the Central Metasedimentary Belt gold "camps", based on age and possible origin of the mineralization. At least 4 broad groupings are present:

- "Orogenic" types are shear-zone hosted systems similar to those observed in Archean greenstone belts. They are typically hosted in metavolcanic sequences, and may be associated with major domain and terrane boundaries.
- "Magmatic" types may be hosted in metavolcanic or carbonate sequences, and are spatially associated with specific mafic or felsic intrusions (e.g., Cordova camp and the Cordova gabbro, Helena camp and Helena trondhjemite stock). These types are more analogous to modern porphyry or manto-type systems.

Table 15.1. Tectonic classification of gold "camps" in the Central Metasedimentary Belt (this study).

Age of Mineralization	Name of Camp (*from* Easton and Fyon 1992)	Tectonic Setting
1282 Ma	Bannockburn camp (western Grimsthorpe domain)	Orogenic
~1270 Ma	Not recognized as a separate type, lumped in with Marble Lake–Harlowe camp (Helena intrusion)	Magmatic
~1250 Ma	Cordova Camp	Magmatic
~1250 Ma	Deloro camp	Magmatic, reworked?
>1160 Ma??	Addington–O'Donnell camp (Grimsthorpe–Mazinaw boundary/Flinton Group association)	Orogenic, reworked
>1160 Ma??	Marble Lake–Harlowe Camp (Flinton Group association)	Orogenic, reworked
~1000 Ma	Lavant–Darling camp (Robertson Lake mylonite zone)	Orogenic, young shear zone

- A second, unconformity-related, orogenic type exists, hosted in mafic metavolcanic rocks or carbonate rocks, but associated near the unconformity with the metaconglomerates and meta-arenites of the Flinton Group. This association may be analogous to the Archean "Timiskaming-hosted" gold deposits. The age of the second orogenic type is difficult to determine. It is likely younger than the maximum depositional age of the Flinton Group, namely 1160 Ma, but has likely been reworked during 1020 Ma high-grade metamorphism in Mazinaw terrane.
- Finally, gold is associated with mafic metavolcanic, mafic metaplutonic, and carbonate rocks in the late-tectonic Robertson Lake mylonite zone. It is unclear if the gold in this zone is the product of a single gold mineralizing event, or represents reworking of pre-existing gold deposits, or both.

URANIUM-LEAD GEOCHRONOLOGY RESULTS

Analytical Procedures

Zircon was separated from the rock samples using standard heavy liquid and magnetic separation techniques. All zircon fractions have had an air abrasion treatment (Krogh 1982). Mineral dissolution in the presence of a mixed ^{205}Pb–^{235}U tracer follows the procedure of Krogh (1973). No chemical separation procedure was performed on the zircons as this is generally considered unnecessary for grains that weigh less then 5 µg. Grains analyzed in this study weighed between 0.6 and 3.1 µg. The dissolved sample solutions were dried down and re-dissolved in 3.1N HCl and the bulk dissolved sample was analyzed in the mass spectrometer.

Lead and uranium were loaded together with silica gel (Gerstenberger and Haase 1998) onto outgassed rhenium filaments. The isotopic compositions of Pb and U were measured using a single collector with a Daly pulse counting detector in a solid source VG354 mass spectrometer. Data are corrected for a mass discrimination of 0.07%/atomic mass units (AMU) and a dead time correction of 19.5 ns. The thermal source mass discrimination correction is 0.1%/AMU for both Pb and U. The laboratory blanks for Pb and U are usually less than 1 and 0.1 pg, respectively, but small amounts of common Pb can be introduced during sample loading into dissolution vessels, or any other part of the procedure thereafter until samples are under vacuum in the thermal source. In this study, the total common Pb of each analysis ranged from 0.7 to 2.8 pg and was attributed to laboratory Pb, thus no correction for initial common Pb from geological sources was made.

Error estimates were calculated by propagating known sources of analytical uncertainty for each analysis including ratio variability (within run), uncertainty in the fractionation correction (0.038% and 0.015% (1σ) for Pb and U, respectively, based on long-term replicate measurements of the standards SRM982 and CBNM072-6), and uncertainties in the isotopic composition and amount of laboratory blank. Decay constants are those of Jaffey et al. (1971). All age errors quoted in the text and table, and error ellipses in the concordia diagrams are given at the 95% confidence interval. Plotting and line calculations are from Isoplot/Ex (Ludwig 2001) or Davis (1982).

Results are listed in Tables 15.2 and Appendix 15.1, and illustrated in Figures 15.2 and 15.3. Detailed location information for the samples is given in Appendix 15.1.

Table 15.2. Summary of age results from the Grimsthorpe area.

Sample Number	Mean ^{207}Pb/^{206}Pb age	Intercept Age	Preferred Interpretation
04RME-0901	1279.5 ± 3.3 Ma	1280.5 ± 7.6 Ma	1280 ± 3 Ma
04RME-0902	1283.8 ± 1.7 Ma	$1283\ ^{+3}/_{-2}$ Ma	$1283\ ^{+3}/_{-2}$ Ma
04RME-0903	1281.4 ± 2.5 Ma	1281.8 ± 2.8 Ma	1282 ± 3 Ma

04RME-0901 Felsite, Chard–Dillman Property

The sample was a mineralized felsite from the Grimsthorpe Group, taken from a trench on the Chard–Dillman Property. Four analyses (SK18P25-28), one single grain and 3 multi-grain, give consistent ^{207}Pb/^{206}Pb ages, a range in discordance (0.5%, 0.7%, 0.9% and 1.8%), and an upper intercept age of 1280.5±7.6 Ma (MSWD=0.16, 95% probability of fit) (*see* Figure 15.2), which is indistinguishable from the weighted mean ^{207}Pb/^{206}Pb age of 1279.5±3.3 Ma (MSWD=0.14, 95% probability of fit).

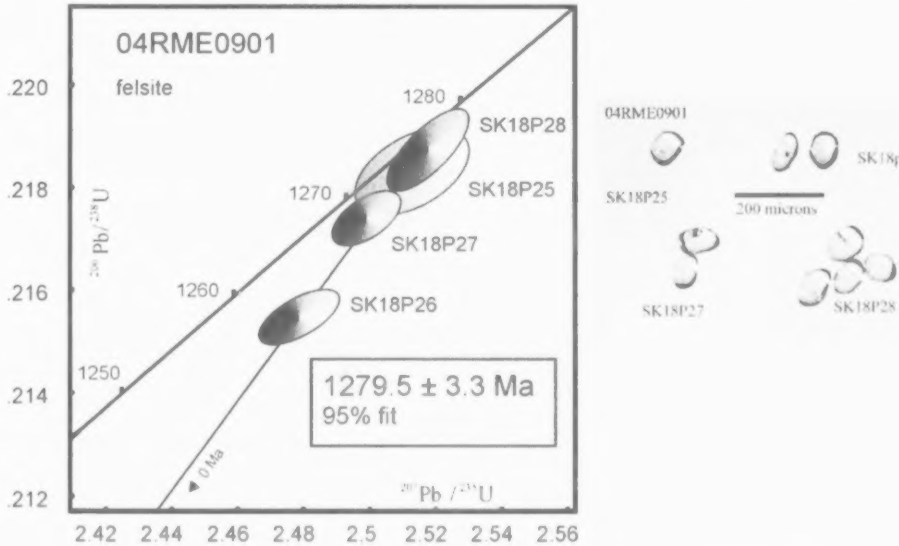


Figure 15.2. Concordia diagram for U/Pb zircon analyses for sample 04RME-0901.

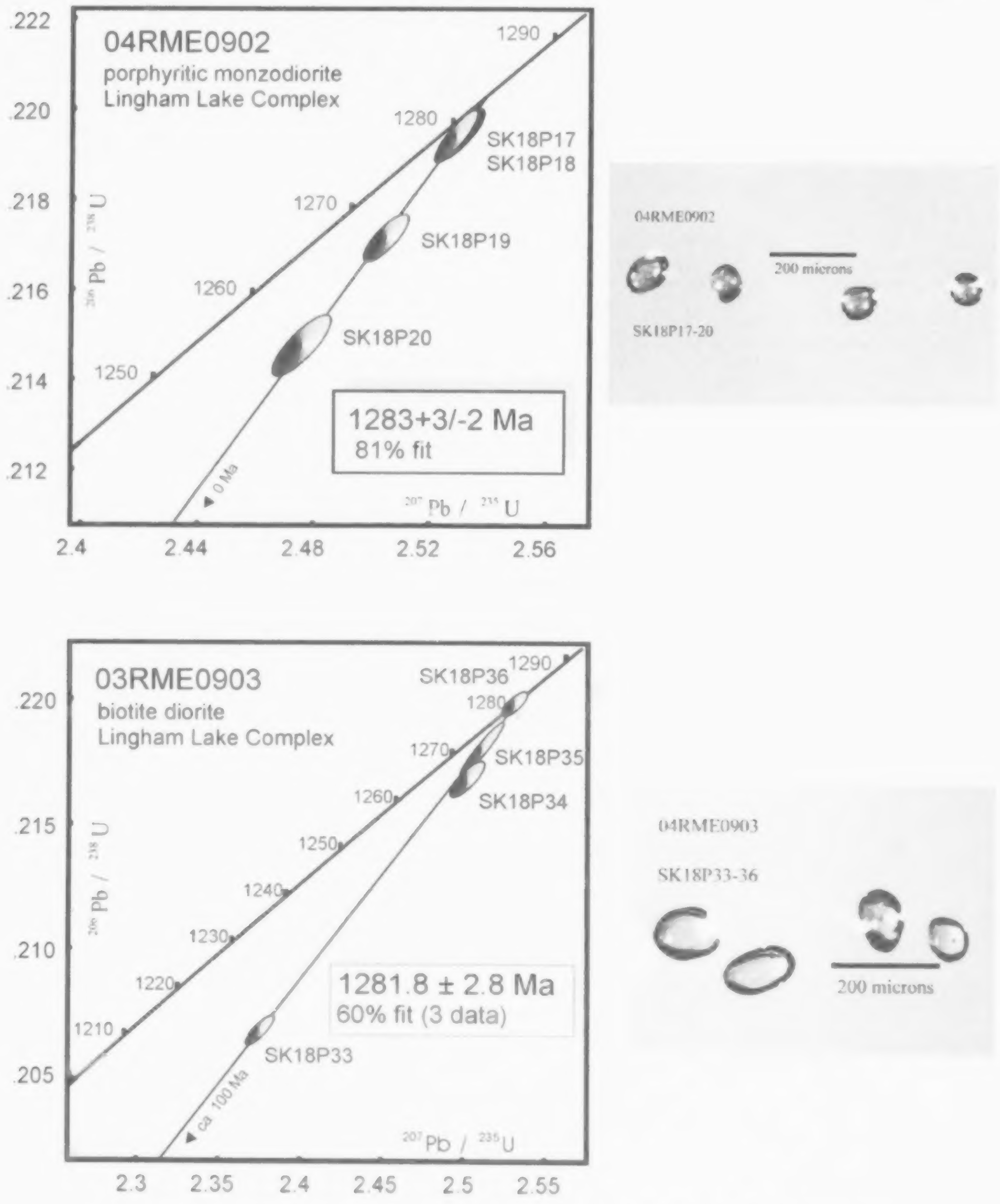


Figure 15.3. Concordia diagram for U/Pb zircon analyses for samples 04RME-0902 and 04RME-0903.

04RME-0902 Monzodiorite, Lingham Lake Intrusive Complex

The sample was a porphyritic monzodiorite from the western margin of the Lingham Lake intrusive complex, roughly 400 m west of where the monzodiorite cuts across the Moira River shear zone and from an intrusion breccia hosting rocks of the shear zone. Four single zircon grains (SK18P17-20) give data that are 0.4%, 0.4%, 1.5%, and 2.5% discordant with consistent $^{207}Pb/^{206}Pb$ ages. A best-fit line through the data gives an upper intercept age of 1283+3/–2 Ma (81% fit) and an approximate zero-age lower intercept (*see* Figure 15.3). This is identical to the weighted mean age of 1283.8±1.7 Ma (MSWD=0.17, 91% probability of fit) using all 4 data points, and 1283.4±2.2 Ma (MSWD=0.13, 74% probability of fit) using the 2 least discordant data.

04RME-0903 Biotite Diorite, Lingham Lake Intrusive Complex

The sample was a biotite diorite, typical of the main phase of the Lingham Lake intrusive complex. The sample was collected from the western margin of the Lingham Lake intrusive complex, and relative age relationships indicate that the biotite diorite is slightly younger than the porphyritic monzodiorite. Four single zircon crystals give concordant (SK18P36) and variably discordant U/Pb data (SK18P33-35). A line calculated through 3 data points (excluding SK18P34 which has a slightly older $^{207}Pb/^{206}Pb$ age) gives an upper intercept age of 1281.8±2.8 Ma (60% probability of fit) and has a lower intercept of about 100 Ma (*see* Figure 15.3). This is the best estimate of the age of the intrusion and is indistinguishable from the weighted mean $^{207}Pb/^{206}Pb$ age of all 4 data points (1281.1±5 Ma, MSWD=2.4) and of the 2 least discordant data (1281.4±2.5 Ma, MSWD=0.09).

DISCUSSION

The 3 samples yield the same age (*see* Table 15.2), within error, and indicate that gold mineralization and shear zone development occurred within a short interval at 1282 Ma. This is based on the fact that the felsite was emplaced, sheared and mineralized, with subsequent intrusion of the shear zone by rocks of the Lingham Lake intrusive complex. Samples 04RME-0901 and 04RME-0902 bracket the relative time range of these events, and yield indistinguishable ages. As a consequence, emplacement of the Lingham Lake intrusive complex may have played a role in driving the hydrothermal alteration system related to carbonate flooding, quartz veining, and shear zone generation.

The age of the felsite closely matches the 1279±3 Ma age from a non-mineralized felsite from Tudor Township reported by Heaman et al. (1987), and suggests that the 1280±3 Ma age for sample 04RME-0901 reflects the time of felsite emplacement, not a subsequent event. The age of the Lingham Lake intrusive complex, is slightly older than expected, but is consistent with field relationships (Easton and Ford 1994) that indicate it is slightly older than the Elzevir tonalite, for which an age of 1270 Ma (Heaman et al. 1987) has been obtained.

The ages reported here are among the oldest reported from the Central Metasedimentary Belt, with the only reported older age (1287 $^{+10.7}/_{-3.2}$ Ma: Davis and Bartlett 1988) from volcanic rocks within the Belmont domain. The ages reported herein are from rock units emplaced relatively late into the mafic metavolcanic and mafic intrusive rocks that form the Grimsthorpe domain and, as such, only provide a minimum age for deposition of the Grimsthorpe Group and the Canniff Complex.

REFERENCES

Carter, T.R. and Colvine, A.C. 1985. Metallic mineral deposits of the Grenville Province, southeastern Ontario; Canadian Institute of Mining and Metallurgy Bulletin, v.78, March, p.95-106.

Christie, B.J. 1990. Soil survey assessment report, Gilmour Property; Tweed Resident Geologist's office, assessment file Grimsthorpe #24, 12p.

Davis, D.W. 1982. Optimum linear regression and error estimation applied to U-Pb data; Canadian Journal of Earth Sciences, v.19, p.2141-2149.

Davis, D.W. and Bartlett, J.R. 1988. Geochronology of the Belmont Lake Metavolcanic Complex and implications for crustal development in the Central Metasedimentary Belt, Grenville Province, Ontario; Canadian Journal of Earth Sciences, v.25, p.1751-1759.

Easton, R.M. 1992. The Grenville Province; *in* Geology of Ontario, Chapter 19, Ontario Geological Survey, Special Volume 4, Part 2, p.713-904.

——— 2004. Geology, tectonic history and controls on gold mineralization in western Grimsthorpe domain, Central Metasedimentary Belt, Grenville Province; *in* Summary of Field Work and Other Activities, Ontario Geological Survey Open File Report 6145, p.14-1 to 14-21.

Easton, R.M. and Ford, F.D. 1994. Geology of the Grimsthorpe area; Ontario Geological Survey Open File Report 5894, 153p.

Easton, R.M. and Fyon, A.J. 1992. Metallogeny of the Grenville Province; *in* Geology of Ontario, Chapter 24, Ontario Geological Survey, Special Volume 4, Part 2, p.1216-1252.

Gerstenberger, H. and Haase, G. 1997. A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations; Chemical Geology, v.136, p.309-312.

Heaman, L.M., Davis, D.W., Krogh, T.E., and Lumbers, S.B. 1987. Geological evolution of the Central Metasedimentary Belt (CMB), Ontario: a U-Pb perspective; Geological Association of Canada–Mineralogical Association of Canada, Program with Abstracts, v.12, p.A-54.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C. and Essling, A.M. 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U; Physical Review, v.4, p.1889–1906.

Krogh, T.E. 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations; Geochimica et Cosmochimica Acta, v.37, p.485-494.

———1982. Improved accuracy of U-Pb ages by the creation of more concordant systems using an air abrasion technique; Geochimica et Cosmochimica Acta, v.46, p.637-649.

Ludwig, K.E. 2001. Users manual for Isoplot/Ex v.2.49: a geochronological toolkit for Microsoft® Excel; University of California–Berkeley, Berkeley, California, Berkeley Geochronology Center, Special Publication No. 1a.

Sangster, A.L. and Bourne, J. 1982. Geology of the Grenville Province, and regional metallogenesis of the Grenville Supergroup; *in* Precambrian sulphide deposits, Geological Association of Canada, Special Paper 25, p.91-125.

Sangster, A.L., Gauthier, M. and Gower, C.F. 1992. Metallogeny of structural zones, Grenville Province, northeastern North America; Precambrian Research, v.58, p.401-426.

Appendix 15.1. Uranium-lead (U/Pb) zircon geochronology data for rocks from the Grimsthorpe area.

Analysis no.	Fraction	Weight (mg)	U (ppm)	Pb (ppm)	Th/U	Pb tot (pg)	Pb com (pg)	206Pb/ 204Pb	207Pb/ 204Pb	206Pb/ 238U	2σ	207Pb/ 235U	2σ	206/238 Age (Ma)	2σ	207/235 Age (Ma)	2σ	207/206 Age (Ma)	2σ	% Disc	Corr Coeff
04RME-0901 Felsite (297300E, 4962818N, Zone 18, NAD83)																					
sk18p25	1 colourless, euhedral, translucent	0.0006	229	51	0.36	30.7	1.4	1378.5	129.2	0.21830	0.00059	2.5129	0.0158	1272.9	3.1	1275.8	4.6	1280.6	10.2	0.7	0.573
sk18p26	2 colourless, euhedral, translucent	0.0007	231	51	0.34	35.5	1.2	1934.0	175.5	0.21548	0.00048	2.4787	0.0119	1257.9	2.6	1265.8	3.5	1279.3	7.4	1.8	0.632
sk18p27	2 colourless, euhedral, translucent	0.0009	325	73	0.39	65.4	1.8	2294.2	205.4	0.21740	0.00047	2.4991	0.0104	1268.1	2.5	1271.8	3.0	1278.0	6.2	0.9	0.663
sk18p28	4 colourless, euhedral, translucent	0.0026	182	41	0.38	106.4	2.8	2408.4	215.2	0.21873	0.00058	2.5178	0.0108	1275.2	3.1	1277.2	3.1	1280.6	5.9	0.5	0.709
04RME-0902 Porphyritic monzodiorite, Lingham Lake intrusive complex (297780E, 4958815N, Zone 18, NAD83)																					
sk18p17	1 equant, euhedral, gem, pink, translucent	0.0021	372	85	0.44	179.0	1.1	10185.9	865.6	0.21940	0.00058	2.5288	0.0074	1278.7	3.1	1280.4	2.1	1283.2	2.8	0.4	0.877
sk18p18	1 equant, euhedral, gem, pink, translucent	0.0013	359	82	0.44	106.7	1.4	4571.8	396.4	0.21943	0.00057	2.5302	0.0083	1278.9	3.0	1280.8	2.4	1283.9	3.6	0.4	0.830
sk18p19	1 equant, euhedral, gem, pink, translucent	0.0013	352	79	0.42	103.2	1.3	4800.4	415.7	0.21714	0.00053	2.5049	0.0078	1266.8	2.8	1273.5	2.2	1284.8	3.6	1.5	0.805
sk18p20	1 equant, euhedral gem, pink, translucent	0.0012	388	86	0.40	103.3	1.9	3371.9	296.1	0.21475	0.00068	2.4759	0.0102	1254.1	3.6	1265.0	3.0	1283.7	4.6	2.5	0.822
04RME-0903 Biotite diorite, Lingham Lake intrusive complex (298188E, 4957696N, Zone 18, NAD83)																					
sk18p33	1 pale brown gem, 2:1 prism	0.0031	233	49	0.37	153.2	2.4	4064.6	352.9	0.20673	0.00060	2.3757	0.0087	1211.4	3.2	1235.3	2.6	1277.4	3.9	5.7	0.842
sk18p34	1 pale brown gem, 2:1 prism	0.0025	100	22	0.38	55.5	1.1	3303.6	290.6	0.21682	0.00073	2.5024	0.0105	1265.1	3.8	1272.7	3.1	1285.7	4.9	1.8	0.803
sk18p35	1 pale brown gem, 2:1 prism	0.0021	218	49	0.38	102.7	1.1	6094.2	523.2	0.21802	0.00109	2.5112	0.0134	1271.4	5.8	1275.3	3.9	1281.7	3.2	0.9	0.842
sk18p36	1 pale brown gem, 2:1 prism	0.0013	166	36	0.26	47.4	0.7	4181.5	363.3	0.21984	0.00050	2.5311	0.0079	1281.0	2.6	1281.0	2.3	1281.0	3.9		0.767

Notes: Pb tot - Total amount of radiogenic Pb. Pb com - common Pb, assuming all has blank isotopic composition. ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb corrected for fractionation and common Pb in the spike. Pb/U and Pb/Pb also corrected for blank. Th/U calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{206}Pb age assuming concordance. %Disc - per cent discordance for the given ^{207}Pb/^{206}Pb. Uranium decay constants are from Jaffey et al. (1971). Sample locations are provided as Universal Transverse Mercator co-ordinates in North American Datum 1983 (NAD83).

16. Project Unit 00-101. Summary of Geophysical Projects and Activities

D.R.B. Rainsford[1] **and T.L. Muir**[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Support of the bedrock mapping program, through the integration of geology and geophysics, has been the focus of efforts this year. Support has also been provided to the Sedimentary Geoscience Section to aid with surficial studies and geophysical assistance has been given to the Resident Geologist Program. Collaborative interpretation of geoscience data is emphasized. Improved interpretations of the subsurface have been achieved through the use of three-dimensional (3D) inversion potential field modelling and visualization software. New information related to the Discover Abitibi projects added to the geophysical data publicly available. In addition, client support and training activities have continued throughout the year.

Geophysical projects and activities for 2005 covered the following areas:

1. Support for the bedrock mapping program
2. Data acquisition
3. Modelling, inversion and visualization
4. Data distribution
5. Training and education
6. Other activities

SUPPORT FOR THE BEDROCK MAPPING PROGRAM

Support for bedrock mapping projects in the Precambrian Geoscience Section of the Ontario Geological Survey continued to be a priority. Support included the preparation of georeferenced digital images and paper maps of geophysical data, in areas of interest, prior to the start of field work. Typically, these maps and images comprise magnetic (and derivatives), electromagnetic, gravity (and derivatives), electrical resistivity/conductivity and digital elevation products. These data are drawn from published archive data sets held by the Ministry of Northern Development and Mines (MNDM), the Geological Survey of Canada and from other sources. The choice and presentation of images are tailored to meet the requirements of each project and all images are formatted for use with geographic information systems (GIS) software.

Where possible, the geophysical data are discussed with geologists before field work begins and specific problems requiring further investigation are identified. In some cases, modelling of specific features is undertaken using 3D inversion or other software.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.16-1 to 16-4.

© Queen's Printer for Ontario, 2005

Building on an approach adopted for the Fort Hope greenstone belt, a two-day interpretation workshop was held in order to collaboratively interpret geological and geophysical data for the Cobalt–Temagami area compilation project. The workshop resulted in better definition of the geological contacts and units in areas of poor exposure; inferred unmapped structures; and identification of areas where existing compilation data are in conflict with detailed geological mapping and/or geophysical data.

Geophysical support was provided for the following projects during 2005:

- Caribou greenstone belt surficial studies (project 05-019)
- Cobalt–Temagami area compilation (project 95-024)
- Huron North area (project 95-014)
- Powell–Montrose–Bannockburn townships area (project 05-005)
- Shaw Dome area compilation (project 00-011)
- Hudson Bay–James Bay Lowlands Archean Substrate (projects 98-006 and 98-007)
- Opikeigen Lake area (project 04-006)
- South and Central Swayze areas (projects 02-012, 03-018)
- West-central Nipigon Embayment (project 03-304)
- Western Nipigon Embayment (project 03-001)

MODELLING, INVERSION AND VISUALIZATION

Greater use has been made of modelling inversion and visualization tools for the interpretation of potential field data and communication of model results. While magnetic modelling was employed for the Hudson Bay–James Bay lowlands project and the Powell–Montrose–Bannockburn area project, the greatest use of 3D inversion of gravity and magnetic data was made for the Nipigon Embayment project area.

The work, which was done in conjunction with L.E. Reed, geophysical consultant, for the Lake Nipigon Region Geoscience Initiative, was carried out to gain a better understanding of specific features (i.e., particular magnetic and gravity anomalies) and to gain insight into regional structures. The modelling, which was performed using the University of British Columbia Geophysical Inversion Facility smooth-model inversion software, was run in an unconstrained manner (i.e., without a predetermined starting model). The results were displayed using WinDisp visualization software developed by Scientific Computing and Applications. Models were displayed along with surface geology and interpreted with reference to the physical property data (magnetic susceptibility and specific gravity) collected in the area. The inversion modelling was able to show the geometry of geological features in the basement below thick Proterozoic diabase sills; provide a context for isolated inliers of Archean mafic rocks exposed through the Nipigon sill; and yield information on large-scale structures. The results from some of these models are presented in MacDonald, Tremblay and Easton (2005). The results of all the Nipigon area inversion models are to be included in an Open File Report, scheduled to be released in December 2005.

As part of OMET project P03-04-050, carried out by MIRARCO (Mining Innovation, Rehabilitation and Applied Research Corporation, at Laurentian University) to investigate the benefits of virtual reality and common earth modelling for efficient data interpretation, the results from detailed modelling of specific features in the Nipigon area were imported into GoCAD 3D visualization software along with other geoscience data for display in MIRARCO's virtual reality lab (VRL). While the results were visually spectacular and the VRL provided a good forum for the discussion of model results, the scarcity of subsurface geological information produced little additional benefit over the desktop computer-based visualization tools already employed.

DATA DISTRIBUTION

Airborne geophysical survey data were released by the OGS in two publications during 2005. The Matheson area airborne electromagnetic data, initially released in 2000, were reprocessed to improve and extract more information, and subsequently released as Geophysical Data Set (GDS) 1055. This work was done by Condor Consulting Inc. as part of the Discover Abitibi Initiative. Previously collected airborne data (1979–1981) for the Squirrel River–Otter Rapids–Moose River areas, in the James Bay Lowlands area, were acquired from Aur Resources Inc. and digitally reprocessed for release as GDS 1228. In addition, two magnetic images covering the area of the Abitibi Greenstone Belt Compilation (Ayer, Trowell and Josey 2004; Ayer et al. 2005) were published at 1: 250 000 scale. The magnetic images incorporate single master aeromagnetic data for Ontario (ERLIS Data Set 1036), magnetic supergrid data (GDS 1037) and data from the Round Lake Batholith area (GDS 1048) acquired under the Discover Abitibi Initiative. The publications are summarized in Table 16.1.

Table 16.1. Releases of airborne geophysical publications in 2005.

Survey Name	Publication No.	Release Date	Survey For	Survey By	Survey Type	Line-kilometres
Data Reassessment: Matheson Area	GDS 1055	July	Discover Abitibi	Spectrem Air	Airborne Magnetic, Electromagnetic Spectrem$_{2000}$	10 805
Squirrel River – Otter Rapids – Moose River Areas	GDS 1228	December	OGS	Questor Surveys and Northway Survey Corp.	Airborne Magnetic	27 310
Abitibi Greenstone Belt	Map 81 952	April	Various	Various	Aeromagnetic compilation – residual magnetic field	N/A
Abitibi Greenstone Belt	Map 81 953	April	Various	Various	Aeromagnetic compilation – greyscale shaded magnetic relief	N/A

TRAINING AND EDUCATION

A full-day course, covering interpretation of airborne magnetic, electromagnetic, gravity and radiometric surveys was presented to staff of the Precambrian and Sedimentary Geoscience sections of the OGS. The objective was to inform geoscientists of the methods and procedures available to them in the course of undertaking their field projects.

A half-day course, covering the interpretation of airborne electromagnetic and magnetic surveys was presented to the Sudbury Prospectors and Developers Association in Sudbury. The objective of the course was to provide prospectors with the understanding to make basic interpretations of airborne geophysical maps for mineral exploration purposes. The course comprised oral presentations and practical exercises.

As part of the exploration geophysics course at Laurentian University, a half-day airborne geophysical interpretation workshop is scheduled for December 2005.

The results of the geophysical surveys and inversion modelling, done under the auspices of the Lake Nipigon Geoscience Initiative, were presented at the 2005 Canadian Institute of Mining and Metallurgy annual meeting in Toronto. A presentation, on the use of Public Domain geophysics, was given at the Ontario Exploration and Geoscience Symposium in December 2004 in Toronto.

GEOPHYSICAL ATLAS

The web-based Geophysical Atlas, which shows the disposition of public domain geophysical data in Ontario, has continued to be maintained as new data sets are released. The Geophysical Atlas may be accessed at the following Web site:

http://www.mndm.gov.on.ca/mndm/mines/ogs/gpxatlas/Default_e.asp

We recommend visiting this site to gather information about surveys that are available in general, or surveys of particular interest.

OTHER ACTIVITIES

Client support has been provided to members of the public throughout the year. This activity comprises responding to requests for information about the availability of geophysical data within Ontario; questions concerning the use of geophysical data sets; and putting clients with specific needs in touch with geophysical service providers. As part of the on-going effort to generate metadata for all OGS publications, metadata records have been created for all digital geophysical data sets published by the OGS. This will result in improved discoverability of Ontario geophysical data through a variety of metadata search engines.

REFERENCES

Ayer, J.A., Trowell, N.F. and Josey, S. 2004. Geological compilation of the Abitibi greenstone belt; Ontario Geological Survey, Miscellaneous Release—Data 143.

Ayer, J.A., Berger, B.R., Hall, L.A.F., Houlé, M.G., Johns, G.W., Josey, S., Madon, Z., Rainsford, D., Trowell, N.F. and Vaillancourt, C. 2005. Geological compilation of the central Abitibi greenstone belt: Kapuskasing Structural Zone to the Quebec border; Ontario Geological Survey, Preliminary Map P.3565, scale 1:250 000.

MacDonald, C.A., Tremblay, E. and Easton R.M. 2005. Precambrian geology of the west-central map area: Nipigon Embayment: northwestern Ontario, Lake Nipigon Region Geoscience Initiative, Ontario Geological Survey, Open File Report 6164, 49p.

17. Project Unit 95-024. A Re-evaluation of the RADARSAT-1 Geological Interpretation of the Lightning River Area, Abitibi Greenstone Belt, Ontario Under the Upcoming RADARSAT-2 Program (SOAR)

N.F. Trowell[1] and Z.B. Madon[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

In 1999, the authors published the results of a study of the Lightning River area that used as one of its main components radar data acquired from Canada's RADARSAT-1 satellite (Madon et al. 1999). This study demonstrated that RADARSAT data were somewhat useful for geomorphologic interpretation especially at the regional scale, but that, in general, it was not as good as either available airborne radar data or digital elevation model (DEM) data (Madon et al. 1999). Combining it with other available data sets, such as airborne magnetic surveys, did allow for confirmation of regional structural interpretations, but did not lead to identification of new geological structures.

RADARSAT-2 PROGRAM

The RADARSAT-2 satellite, which is a partnership between the Canadian Space Agency (CSA) and MacDonald Dettwiler and Associates (MDA), is scheduled to be launched in 2006. It will have several additional and enhanced abilities such as finer resolution, a range of resolutions, swaths and incident angles, faster processing and delivery, increased geometric accuracy and multi-polarization that are especially useful for geological mapping (Table 17.1).

Table 17.1. Geological applications of RADARSAT-2 data with specific reference to multi-polarization (*from* http://www.radarsat2.info/application/app_overview.asp [accessed September 29, 2005]).

Terrain Mapping	Ultra-fine	Permit more detailed mapping
	Dual polarization/ quad polarization	Expected to improve the mapping of surficial deposits and rock units in vegetated terrains because of the differences in the structural properties which the varying polarizations can observe
	HV	Mapping recharge terrains in arid environments, HV provided better contrast than both HH and VV
Structure	HV	More sensitive to areas of extreme surface roughness or where abrupt changes in relief occur. Bedrock fracture zones and fault scarps are highlighted by much stronger contrast relative to the surroundings than in like-polarized
Lithology	HH/HV or VV/HV	Combination provides for better discrimination of different geological units

Abbreviations: HH, horizontal transmit – horizontal receive polarization; HV, horizontal transmit – vertical receive polarization; VV, vertical transmit – vertical receive polarization.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.17-1 to 17-2.

© Queen's Printer for Ontario, 2005

The authors this year had their SOAR[1] proposal approved and will receive RADARSAT-2 data for the same geographic area (Figure 17.1) as was studied in 1999 (Madon et al. 1999). A comparative study will be done when the images are received in either late 2006 or 2007.

A report, "Applications Potential of RADARSAT-2 A Preview (van der Sanden and Ross 2001), is available at http://www.radarsat2.info/application/appl_index.asp [accessed September 29, 2005] under the heading "CCRS Application Handbook".

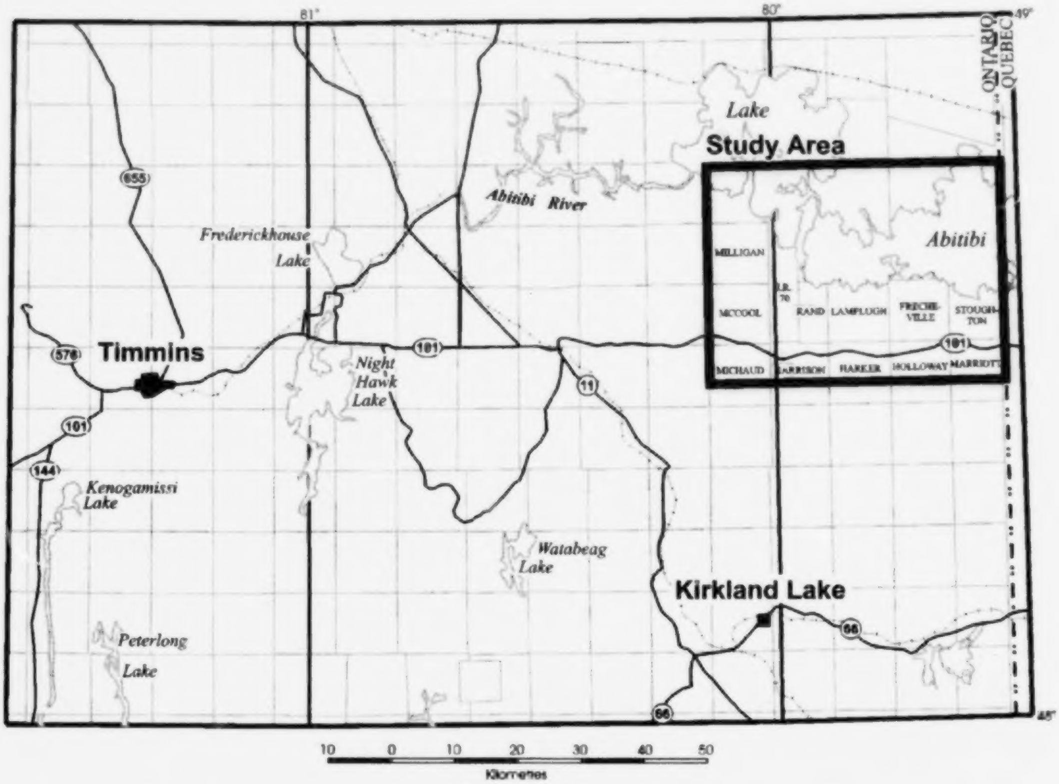

81°
80°
49°
48°
ONTARIO
QUEBEC
Lake
Study Area
Abitibi
Abitibi River
Frederickhouse Lake
655
576
Timmins
101
144
11
66
Night Hawk Lake
Kenogamissi Lake
Watabeag Lake
Kirkland Lake
Peterlong Lake
MILLIGAN
I.R. 70
MCCOOL
RAND
LAMPLUGH
FRECHEVILLE
STOUGHTON
MICHAUD
GARRISON
HARKER
HOLLOWAY
MARRIOTT
10 0 10 20 30 40 50
Kilometres

Figure 17.1. Location map for the Lightning River area.

REFERENCES

Madon, Z., Trowell, N.F., Berger, B. and Ayer, J.A. 1999. Geological investigation and data integration of "typical" Canadian Shield terrain using airborne and satellite imagery including RADARSAT Radar–Lightning River area, Abitibi greenstone belt, Ontario; Canadian Journal of Remote Sensing, v.25, no.3, p.229-244.

Van der Sanden, J.J. and Ross, S.G. (eds.) 2001. Applications potential of RADARSAT-2: A preview; Natural Resources Canada–Canada Centre for Remote Sensing, Ottawa, Ontario, report compiled for and with funding from the Canadian Space Agency, 117p., available at http://www.radarsat2.info/application/radarsat-2report.pdf [accessed September 29, 2005].

---

[1] The Science and Operational Applications Research for RADARSAT-2 Program (SOAR) is a joint partnership program between RADARSAT International–MacDonald Dettwiler and Associates (MDA) and the Canadian Government through the Canadian Space Agency (CSA) and the Natural Resource Canada's Canada Centre for Remote Sensing (CCRS).

18. Project Unit 04-019. Towards a Common Digital Data Model for Geological Mapping: Recent Developments and Issues to Address

Z.B. Madon[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Precambrian Geoscience Section of the Ontario Geological Survey (OGS) is continuing its work in developing a common geological data model for the next generation of digital bedrock geology maps and other derivative geoscience products. This work is essential in maintaining and enhancing Ontario's competitiveness with its traditional client base in mineral exploration, mining and environmental studies. An additional objective will be to broaden our client base by reaching out and responding to the needs of non-geologists involved with resource and land management, community services and infrastructure management.

With an increasing use of the internet to communicate and disseminate information of all types, clients will demand that more and more of our products be made available on-line. There is an ever increasing popularity for sites such as Google™ Maps and Google™ Earth (http://earth.google.com/), where clients can query an on-line source and retrieve or download information that is relevant and up-to-date. This *use-and-discard* mentality will increase as more and more people turn to the Internet as their primary source of information.

RECENT DEVELOPMENTS

Over the past year, most of the author's efforts were focussed on researching and evaluating existing corporate geological data models from government surveys and expert working groups. The author attended two conferences that presented a number of developments in the area of data modelling and geology: the Digital Mapping Techniques (DMT) workshop hosted by the United States Geological Survey (USGS) and the annual International Association of Mathematical Geologists (IAMG) conference, held in Toronto. The DMT proceedings from 1997 to 2003 are available on-line (http://ngmdb.usgs.gov/Info/dmt/index.html [accessed 29 September 2005]), although the most recent proceedings may not be posted as of publication of this article (December 2005). The IAMG 2005 technical program is available at the conference Web site (http://www.iamgconference.com/ [accessed 29 September 2005]), and generally the IAMG conference proceedings are available to order through the Association's Web site (http://www.iamg.org/).

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.18-1 to 18-7.

© Queen's Printer for Ontario, 2005

Some of the recent developments by various organizations, national and international, are summarized below.

Geological Survey of Canada

A new information management (IM) branch has been established at the federal level with a mandate to deliver timely and accurate geological data to a broader client base via the Internet. By reaching more clients who can, in turn, develop new services and products with these data, the value of the original geoscience information is enhanced. While the geological map was the primary output for the survey in the past, emphasis will shift to treating the data upon which these maps are created as the fundamental information assets. The IM branch will be developing a national geospatial data infrastructure with a consistent (i.e., standard) information store. In order for this to succeed, the IM branch will have to foster a culture change in the way Geological Survey of Canada staff collect data and generate information.

Radical changes in information management and project work flow will have to be implemented to prepare geoscience information for dissemination across the Internet. Greater consistency with geoscience terminology and a common geological framework will be required. This 'geological framework' includes a temporal reference (i.e., absolute ages), a conceptual geological unit (i.e., stratigraphic lexicon), earth material (i.e., lithological description) and a spatial reference (Davenport 2005). Science language terminology will require experienced scientists to act as stewards of these vocabularies. "Geologists owe it to themselves and to workers in other sciences to use standard nomenclature" (Travis 1955).

United States Geological Survey

Through its National Geological Mapping Act, the United States Geological Survey (USGS) is at the second phase of the three-phase development of the National Geological Map Database. A comprehensive on-line map catalogue was produced in phase 1. Standards development and implementation is the key theme for phase 2, including completion of the USGS Lexicon, map symbolization, map templates, an ESRI® ArcGIS® geodatabase template for data entry based on the North American Data Model (NADM-C1: Figures 18.1 and 18.2) and science language conventions. The model will be scalable[1], interoperable[2] and contain all the necessary metadata. Phase 3 will involve taking these standards and developing on-line map services through the use of XML (eXtensible Markup Language), GML (Geography Markup Language) and XMML (eXploration and Mining Markup Language).

British Geological Survey

The British Geological Survey (BGS) is continuing its development of a digital field collection system to fulfil their mapping requirements. Their corporate data model is the "backbone" of the system. Because the data model is relatively complex, a *form*-based data capture tool was developed for geologists to use in the field. While the system strives "to guarantee corporate consistency and common standards by structuring our data collection, there must also be a degree of flexibility so that geologists are not unduly constrained … and do not leave field geologists yearning for 'the old days'" (Jordan et al. 2005).

---

[1] expanding the data model to be able to generalize or reclassify the geology based on the scale of observation.

[2] developing a standard vocabulary (data dictionaries or lexicons) and framework among the geological characteristics being described (entity–relationship diagrams).

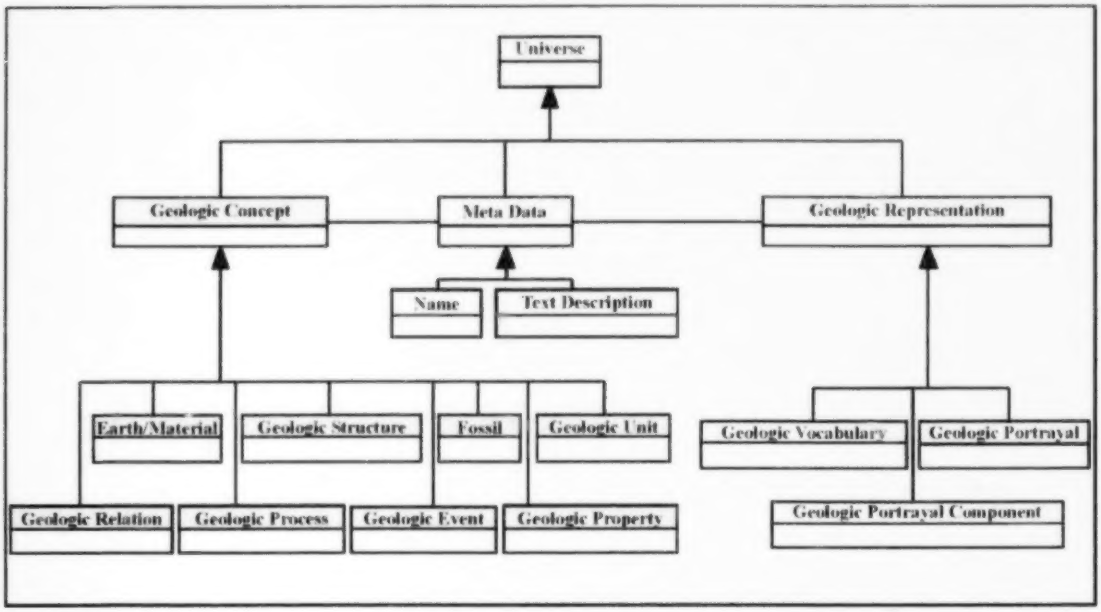
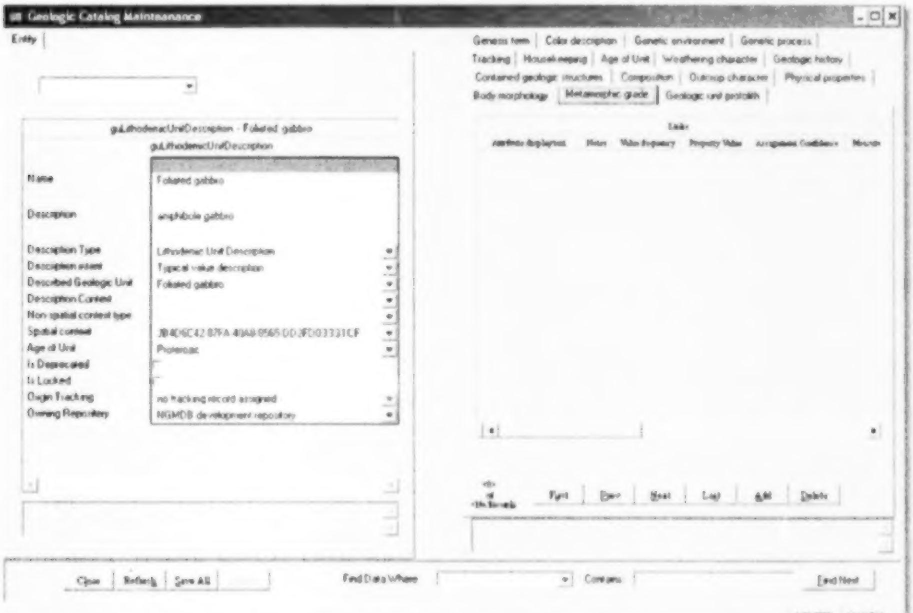

Universe
Geologic Concept
Meta Data
Geologic Representation
Name
Text Description
Earth/Material
Geologic Structure
Fossil
Geologic Unit
Geologic Vocabulary
Geologic Portrayal
Geologic Relation
Geologic Process
Geologic Event
Geologic Property
Geologic Portrayal Component

Figure 18.1. Top level schema for geological objects from the NADM-C1 conceptual model for geological map information (North American Geologic Map Data Model Steering Committee, 2004).


Geologic Catalog Maintenance
Entity
Genesis term
Color description
Genetic environment
Genetic process
Tracking
Housekeeping
Age of Unit
Weathering character
Geologic history
Contained geologic structures
Composition
Outcrop character
Physical properties
Body morphology
Metamorphic grade
Geologic unit protolith
First
Prev
Next
Last
Add
Delete
Close
Refresh
Save All
Find Data Where
Contains
Find Next

Name: Foliated gabbro
Description: amphibole gabbro
Description Type: Lithodemic Unit Description
Description extent: Typical value description
Described Geologic Unit: Foliated gabbro
Description Context:
Non spatial context type:
Spatial context:
Age of Unit: Proterozoic
Is Deprecated
Is Locked
Origin Tracking: no tracking record assigned
Owning Repository: NGMDB development repository

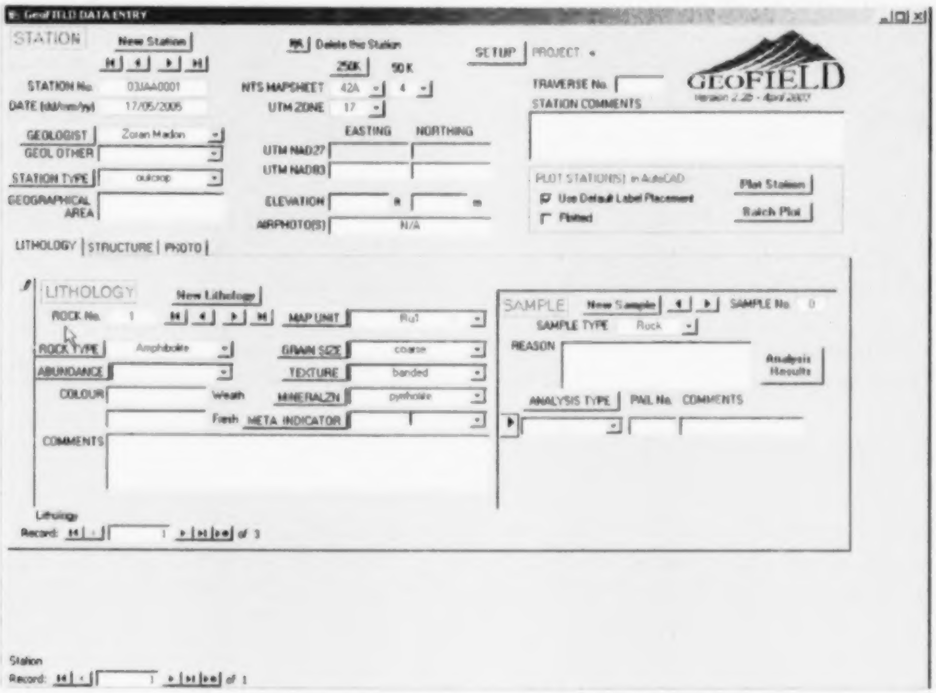
Figure 18.2. Subset of the data entry tool being developed by the USGS that is based on NADM-C1, illustrating the geological unit description editor (Richard, Craigue and Soller 2005).

GeoScience Victoria

GeoScience Victoria (Australia) has developed and implemented a corporate geological data model based on both NADM-C1 and CGI (Commission for the Management and Application of Geoscience Information) conceptual models and principles. GeoScience Victoria completed a *proof of concept* project to build a prototype corporate database that could deliver a variety of geological interpretations as well as allow geographic information system (GIS) tools to use the data for analytical purposes. Design constraints included normalizing the data (i.e., no duplication) as well as using controlled scientific vocabulary. GeoScience Victoria found the use of controlled vocabularies to be very powerful tool: "geological concepts could be efficiently and consistently stored… robust thematic maps could be produced and searches yielded consistent results" (Simons et al. 2005).

Yukon Geological Survey

The Yukon Geological Survey developed a field-based, customized Microsoft® Access 2000 database application (GeoFIELD) to facilitate data entry and production of geological maps (Lipovsky and Colpron 2003; Figure 18.3). The core of the GeoFIELD data model is similar to the original OGS–GSC Fieldlog model that was used extensively by various geological surveys and exploration companies over the last 2 decades. GeoFIELD was designed to be simple and intuitive to use as well as to accommodate a wide spectrum of field studies. It can be used with notebook computers as well as with handheld devices in the field. The GeoFIELD data model conforms to the NADM-C1 schema and ensures consistency in the information collected, thereby improving on data quality. Data collected with GeoFIELD can be easily transferred to a variety of map production software such as AutoCAD® and ArcGIS®.


GeoFIELD DATA ENTRY
STATION
New Station
Delete the Station
SETUP
PROJECT
250K
50K
GEOFIELD
Version 2.2b - April 2007
TRAVERSE No.
STATION COMMENTS
EASTING
NORTHING
UTM NAD27
UTM NAD83
ELEVATION
ft
m
GEOL OTHER
GEOGRAPHICAL AREA
PLOT STATION(S) in AutoCAD
Plot Station
Batch Plot
LITHOLOGY
STRUCTURE
PHOTO
New Lithology
ABUNDANCE
COLOUR
Weath
Fresh
META INDICATOR
COMMENTS
SAMPLE
New Sample
REASON
Analysis Results
ANALYSIS TYPE
PNL No.
COMMENTS

STATION No. 03JAA0001
DATE (dd/mm/yy) 17/05/2005
NTS MAPSHEET 42A 4
UTM ZONE 17
GEOLOGIST Zoran Madon
STATION TYPE outcrop
AIRPHOTO(S) N/A
☑ Use Default Label Placement
☐ Plotted
ROCK No. 1
MAP UNIT Ru1
ROCK TYPE Amphibolite
GRAIN SIZE coarse
TEXTURE banded
MINERALZN pyrrhotite
SAMPLE No. 0
SAMPLE TYPE Rock
Lithology Record: 1 of 3
Station Record: 1 of 1

Figure 18.3. Screen capture of the GeoFIELD data entry tool (Lipovsky et al. 2003), which is available to download at no charge from the Yukon Geological Survey (http://www.geology.gov.yk.ca/publications/openfile/2003/of2003_8d.exe).

ISSUES TO ADDRESS

As we clear the technical and cultural hurdles of developing a robust corporate data model for the next generation of geological information products, three important issues will have to be addressed: data authenticity, long-term preservation of digital information and potential liability for digital products.

Data Authenticity

One of the main advantages of digital geological products is also one of its principal liabilities—that changes to the data can be made very easily. Because of the bewildering array of file formats and data quality, new protocols will have to be established to certify the integrity and authenticity of digital geological information. Duncan (2005b) lists three types of strategies that organizations could use to establish authenticity:

1. public methods (copyright; unique document identifiers, metadata with document authentication)
2. secret methods (digital signatures of survey director, author and senior editor; digital certificates[3], digital watermarks[4])
3. specific technologies (object encapsulation[5], encryption[6])

Data Preservation

Unlike traditional hard-copy maps and reports, which could theoretically be preserved for thousands of years, some of our digital products have a half life of as little as five years (Duncan 2005b). This is especially true for information generated with highly specialized (and generally not widely used) software programs. The preservation of digital data is not only subject to frequent file format changes by software makers, but also to the ever-changing operating system environments and to the constant improvements in storage media: "digital preservation remains largely experimental and replete with the risks associated with untested methods" (Duncan 2005b).

Some of the strategies that have been considered include

1. Production of hard-copy "originals": it is difficult to replicate the depth and richness of a digital product, not to mention its functionality in digital mode.
2. Implementation of standards: the biggest hurdle with this is to reach a consensus on standards; it is generally easier to adopt *de facto* standards (i.e., standards based solely on their widespread use and not because of any officially sanctioned organization).

---

[3] Electronic credit card that establishes your credentials on the Internet; is issued by a certification authority (CA) and contains the organization's name, serial number, expiration date, a copy of the CA's public key and the digital signature of the CA.

[4] A pattern of bits inserted into a digital file that identifies the file's copyright information (author, rights, etc.) - comes from the faintly visible watermarks imprinted on stationery that identify the manufacturer of the stationery.

[5] Hiding all of the details of an object that do not contribute to its essential characteristics.

[6] Process of coding data so that a specific code or key is required to restore the original data.

3. Migration to new software and file formats: this method is probably being used by many organizations today, but will become prohibitively expensive as the volume of digital information products increases exponentially[7].
4. Preservation of obsolete hardware and software systems: also cost prohibitive as spare parts become unavailable and staff with the technical expertise retire.
5. Emulation: encapsulating the digital information along with its software environment and operating system, an approach that has garnered considerable interest among archivists and digital librarians, although not widely used yet.

Potential Liability

By virtue of imposing copyright and/or licensing protection on digital products, government agencies become exposed to increased liability through the use of what can be interpreted as private enterprise type sales. When agencies charge for their data and especially when they charge a recovery fee (i.e., cost for actual collection of data as opposed to cost for reproduction only), government agencies become increasingly exposed to liability. Distribution of information (i.e., geological interpretation) as opposed to distribution of data only (i.e., field notes, outcrop data, etc.) also increases liability. There also appears to be a "myth of machine infallibility" (Duncan 2005a) that creates expectations of high data quality with digital information products. Finally, the recent licencing of professional geoscientists in Ontario creates a potential personal liability for the geologist involved in producing the data.

Types of errors that have been litigated in courts include errors of omission, errors in scale, errors with location of spatial data, errors in the accuracy of attribute data, and inappropriate use of the data or map. Some strategies that have been recommended to protect against litigation include

1. Warnings in the metadata regarding the limitations on the accuracy of the digital product (generic disclaimers commonly used today are of little value in courts, particularly where the disclaimer attempts to completely sever any link between the product and the agency creating it)
2. Accurate metadata
3. Frequently asked questions (FAQ) that show specific examples of the appropriate use of the data
4. Encouraging feedback from clients to report any errors, omissions or other problems with the digital information product and make these errata statements widely available via the Internet or through an e-mail distribution system.

CONCLUSIONS

Progress is being made on several fronts and from several organizations with respect to developing and implementing robust corporate geological data models, including peer-reviewed science language. Fortunately, most geological surveys realize the importance of creating interoperable systems and are, therefore, adopting existing international standards, such as the NADM-C1, in creating data models and developing the necessary data-entry tools for geoscientists. One key element to realizing a successful corporate geological data model will be the human factor: both staff and consumer will have to understand that geological information is more than just 'map data'. Geological information reflects real-world geological concepts and relationships. More and more, the traditional geological map will be merely one of a range of information products and services derived from the model (Simons et al. 2005).

---

[7] The OGS geophysical data sets, originally released in a proprietary format along with a free viewer (Centurion) in the late 1990s, had to be reformatted and re-released a few years later when it was discovered that Centurion would not work in a updated operating system environment.

Issues that have to be addressed as we create digital geological models and disseminate more and more digital products include data authenticity, the potential liability related to these products and their long-term preservation. When compared to paper products and maps, digital geologic information products are characteristically more complex and easily modified, creating challenges in establishing their authenticity. Metadata records will have a very important role for all future digital geological information products, not only to help clients discover the data through Internet queries, but also to certify their authenticity and to reduce potential liability. Long-term preservation of digital information products remains an issue to be resolved.

REFERENCES

Davenport, P.H. 2005. Practical requirements for geoscience information management for Canada; International Association of Mathematical Geologists, Proceedings of IAMG '05: GIS and Spatial Analysis, v.2, p.935-940.

Duncan, I.J. 2005a. Liability for digital datasets created by government agencies; International Association of Mathematical Geologists, Proceedings of IAMG'05: GIS and Spatial Analysis, v.2, p.867-873.

——— 2005b. Authenticity and long term preservation of digital geologic products in archival geoinformatics; International Association of Mathematical Geologists, Proceedings of IAMG '05: GIS and Spatial Analysis, v.2, p.874-879.

Jordan, C., Bee, E., Smith, N., Lawley, R., Ford, J., Howard, A. and Laxton, J. 2005. The development of digital field data collection systems to fulfil the British Geological Survey mapping requirements; International Association of Mathematical Geologists, Proceedings of IAMG '05: GIS and Spatial Analysis, v.2, 886-891.

Lipovsky, P. and Colpron, M. 2003. Digital mapping techniques in the palm of your hand, developments from the Yukon Geological Survey; Geological Association of Canada, GEOLOG, v.32, no.1, p.9-10.

Lipovsky, P.S., Colpron, M. Stronghill, G. and Pigage, L. 2003. GeoFIELD v.2.2. – Data management and map production for the field geologist; Yukon Geological Survey, Open File 2003-8(D), manual included with download, http://www.geology.gov.yk.ca/publications/openfile/2003/of2003_8d.exe [accessed October 6, 2005].

North American Geologic Map Data Model Steering Committee, 2004. NADM Conceptual Model 1.0: a conceptual model for geological map information; Geological Survey of Canada, Open File 4737, 1 CD-ROM. *also* United States Geological Survey, Open-file Report 2004-1334, 58p.

Richard, S.M., Craigue, J.A. and Soller, D.R. 2005. National Geologic Map Database Products: progress report; presentation, United States Geological Survey, Digital Mapping Techniques '05, Workshop, Baton Rouge, Louisiana, August 2005.

Simons, B., Ritchie, A., Bibby, L., Callaway, G., Welch, S. and Miller, B. 2005. Designing and building an object-relational geoscientific database using the North American Conceptual Geology Map Data Model (NADM-C1) from an Australian perspective; International Association of Mathematical Geologists, Proceedings of IAMG '05: GIS and Spatial Analysis, v.2, p.929-934.

Travis, R.B. 1955. Classification of rocks; Quarterly of the Colorado School of Mines, Golden, Colorado, v.50, no.1, 98p.

Sedimentary Geoscience Section

19. Project Unit 04-025. Investigation into the Source of Forest-Ring-Related Natural Gas in Northern Ontario

S.M. Hamilton[1], K.H. Hattori[2] and I.D. Clark[2]

[1]Sedimentary Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Department of Earth Sciences, University of Ottawa, Ottawa, Ontario

---

INTRODUCTION

Forest rings are large circular features that occur in Ontario's northern forests. They can exceed 1.5 km in diameter and are visible due to a change in vegetation at the ring edge and sometimes across the entire ring. Previous work (Hamilton et al. 2004) identified approximately 1600 forest rings by satellite reconnaissance in an area of Ontario encompassing 150 000 km^2 and straddling the physiographic boundary of the James Bay Lowland (Figure 19.1). Earlier work (Hamilton 2000a, 2000b) had indicated that forest rings occur over geological centres of negative-charge and, in at least one case, the source was determined to be methane (CH_4). During 2004, work was carried out to investigate the approximate proportion of rings in Ontario that are centred on methane accumulations. Forest rings sourced by methane may be of interest as possible sources of natural gas. The remaining rings may be of interest to mineral explorationists since other possible sources of negative charge include metallic sulphides, kimberlites, oil and coal (Hamilton 2000a).

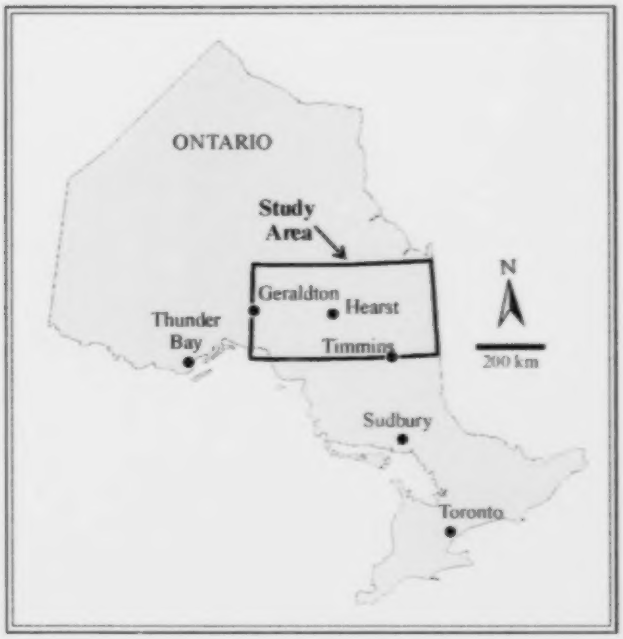


Figure 19.1. Location of study area within Ontario.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.19-1 to 19-4.

© Queen's Printer for Ontario, 2005

The 2004 investigation used a spectral-absorbance laser and reflector system that measures ambient methane concentrations on 11 rings that were considered to be representative of the larger population. Based on the results, it was concluded that the preponderance of rings in northern Ontario overlie methane accumulations. Only 2 of the rings tested failed to demonstrate higher ambient readings of methane inside versus outside the ring.

The source of methane was also of interest in the 2004 study. The six-fold preponderance of rings over shallow glaciomarine sediments, relative to the study area as a whole, suggested microbial production of methane from organic matter in sediments. Isotopic evidence from methane samples collected from one of these rings confirmed this as results showed very low carbon isotope values, indicative of bacterial reduction of CO_2. However, not all the rings are related to marine sediments and there are indications that some are possibly from deeper, structurally controlled bedrock sources (e.g. site R9: Hamilton et al. 2004) or due to accumulations of coal-bed methane as encountered by other workers (e.g., the R4 ring, R. McKinnon, prospector, personal communication, 2004).

During 2005, work was initiated to determine the source of methane on a larger number of rings. Ten of the 11, 2004 sites and 2 additional rings were selected for follow-up isotope work. At each site, drive-point piezometers were installed and diffusion-samplers placed in each. The samplers are due for collection in October and will be analyzed for carbon isotope content. The field methodology and some ancillary field measurements are described below.

STUDY AREA

The locations of 13 rings at which diffusion samplers were installed are shown in Figure 19.2. With the exception of site R2, all have 2 piezometers with a sampler installed in each—one near the geographic centre of the ring and the other towards one edge. On rings where direct measurements of methane concentrations had been made using a photo-ionization-detector (*see* Hamilton et al. 2004), the off-centre piezometer was placed in the area where the highest methane concentrations were measured. A single piezometer and diffusion sampler were installed at site R2, a ring that was determined to be non-methane sourced, based on spectral absorbance measurements completed in 2004.

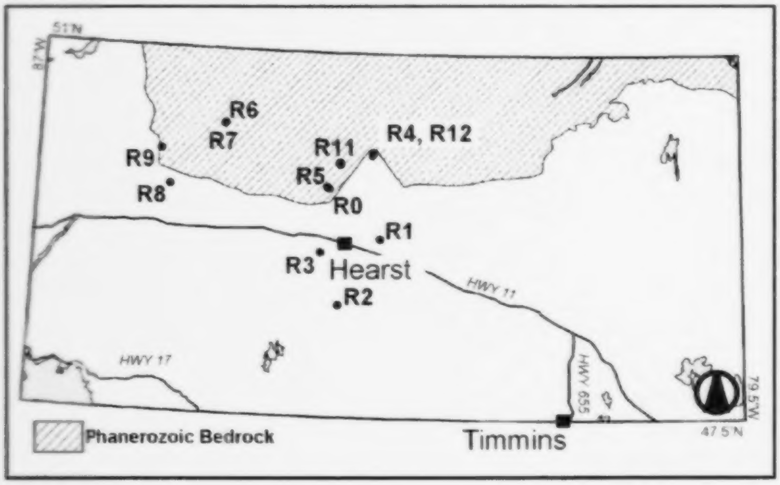


Figure 19.2. Location rings with diffusion samplers installed.

PIEZOMETER INSTALLATION

Stainless-steel drive-point piezometers were installed to a maximum depth of 4.15 m using a slide-hammer. Typically, the depth to the base of peat was established at each site prior to piezometer installation. The piezometer was then assembled and driven down until the top of the screened portion of the drive-point was at least 40 cm below the peat–clay or peat–sand interface. Piezometers (Figure 19.3) consist of a 40 cm long stainless-steel drive point threaded to a ¾" (19 mm) ID steel riser pipe, the length of which varies from site to site. At the top of the drive-point is a barbed-fitting onto which a ½" (13 mm)

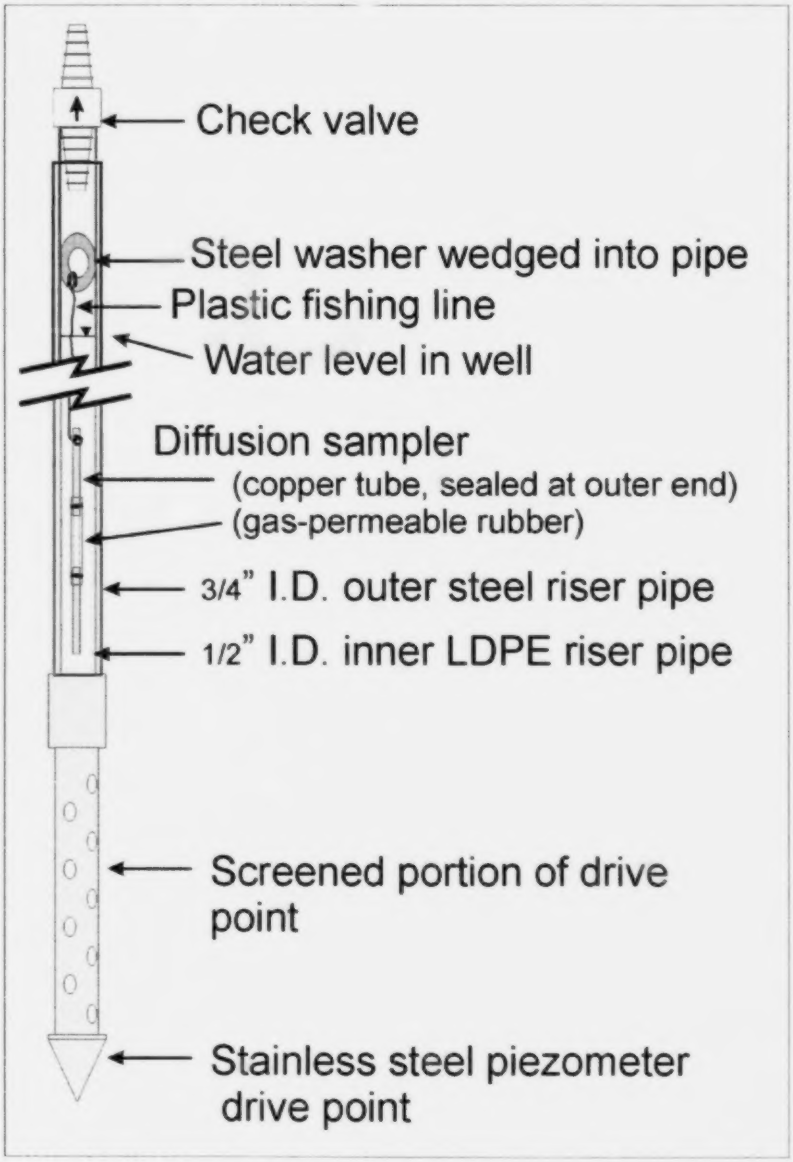

Check valve
Steel washer wedged into pipe
Plastic fishing line
Water level in well
Diffusion sampler
(copper tube, sealed at outer end)
(gas-permeable rubber)
3/4" I.D. outer steel riser pipe
1/2" I.D. inner LDPE riser pipe
Screened portion of drive point
Stainless steel piezometer drive point

Figure 19.3. Design and installation of peizometer and diffusion sampler.

ID low density polyethylene (LDPE) pipe is connected. The LDPE pipe prevents groundwater from contacting the steel riser pipe. At the top of the plastic riser pipe, a check-valve is placed that prevents free exchange between the headspace gases and the atmosphere, but which also allows vapour to vent out from the top of the tube as the water level rises in the piezometer. After piezometer installation, the diffusion sampler is lowered down the well on a line. It consists of a gas-permeable, silicone-rubber tube with 2 copper tubes attached to each end. The outside ends of the copper tubing are sealed with solder. Gases diffuse through the silicone tubing and accumulate in the sealed interior of the rubber and copper.

RESULTS

At the time of writing, the diffusion samplers had not yet been retrieved. They are scheduled for retrieval in the fall of 2005 after being in place for approximately 3 months down-hole. When the samples are collected, clamps are used to crimp-off the copper tubing, which seals the gases in the copper tube for extended periods of time. The gases will be tested for composition and for carbon, hydrogen and possibly helium isotopes. This will give an indication of the providence of the gases in equilibrium with groundwater at each site.

Other measurements and tests done to date, on transects across selected ring edges include

- elevation surveying of the ring edge and base of peat;
- carbonate content of clay (by Chittick);
- moisture content and field-pH of clay;
- chemical composition of clay by inductively coupled plasma emission spectroscopy and mass spectrometry (aqua regia);
- particle size analysis of clay.

The results of all tests and the compositional analysis of gases collected in the diffusion samplers should be available in the spring of 2006.

REFERENCES

Hamilton, S.M. 2000a. Spontaneous potentials and electrochemical cells; *in* Geochemical remote sensing of the subsurface, Chapter 3 of Handbook of exploration geochemistry; Volume 7, Elsevier, Amsterdam, p.81-119.

——— 2000b. Evidence of "earth-batteries" in the development of surface selective leach geochemical anomalies above deeply buried mineral deposits; *in* Proceedings of Mining Millennium 2000, annual meeting of the Prospectors and Developers Association of Canada, Toronto, Ontario, CD-ROM, Article 478, 7p.

Hamilton, S.M., Burt, A.K., Hattori, K.H. and Shirota, J. 2004. The distribution and source of forest ring-related methane in northeastern Ontario; *in* Summary of Field Work and Other Activities, Ontario Geological Survey Open File Report 6145, p.21-1 to 21-26.

20. Project Unit 05-019. Reconnaissance Till Sampling in the Caribou Lake Greenstone Belt Area, Northwestern Ontario

P.J. Barnett[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Caribou Lake greenstone belt, located approximately 15 km north of Lake Nipigon, is currently being explored for gold, copper-nickel-platinum group elements (PGE) and rare metal pegmatites (Smyk et al. 2005). Its mineral potential has not yet been fully evaluated. At present, the "area has an under-appreciated potential for a variety of … mineral deposits … including lode gold, volcanogenic massive sulphide copper-zinc, orthomagmatic copper-nickel and rare metal-bearing pegmatites" (Smyk et al. 2005, p.26). A number of recently opened forest access roads into the area provide the opportunity to gain access to a large part of the greenstone belt to observe fresh exposures of bedrock and surficial sediments for mapping and sampling. The value of prospecting along newly opened forest access roads is emphasized by the discovery of the Kilometre 61 property (Smyk et al. 2005). "The discovery of the Cu-Mo-Au-Ag-mineralized porphyry was made by prospectors S. and M. Stares in 2002 in float boulders and outcrops along the newly constructed logging road" (Smyk et al. 2005, p.25). This example also emphasizes the contribution of drift prospecting to locating areas of mineralized bedrock.

The current project involves regional mapping of the surficial geology and till sampling for heavy mineral indicator and geochemical analysis, over a part of the Caribou Lake greenstone belt located north of Lake Nipigon (Figure 20.1). The study area is portrayed on 4, 1:50 000-scale National Topographic System (NTS) maps 52 I/07, 52 I/08, 52 I/09 and 52 I/10. The study will provide guidance in the interpretation of results from overburden sampling programs in this area and regional information on the mineral potential of this part of the Caribou Lake greenstone belt. The area under investigation is an area of complex interplay between fluctuating glacial margins.

GEOLOGICAL BACKGROUND

The study area straddles the boundary between the English River and Wabigoon subprovinces of the Superior Province (*see* Figure 20.1). The Pashkokogan Lake fault, which marks this boundary, separates the Archean migmatitic metasedimentary diatexitic granite-granodioritic rocks of the English River Subprovince from Archean supracrustal rocks of the Caribou Lake greenstone belt and tonalitic plutons of the Wabigoon Subprovince (Percival et al. 2002; Stott et al. 2002).

The Caribou Lake greenstone belt consists primarily of massive to pillowed basalts, iron formation and komatiite with minor amounts of conglomerate (Percival et al. 2002). Proterozoic Keweenawan-age diabase (gabbro) dikes and sills cut the Archean rocks in the study area.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.20-1 to 20-5

© *Queen's Printer for Ontario, 2005*

Very little mapping of the bedrock geology has been undertaken to date within the study area. This was due, in part, to the poor access and exposure. In 1968, Pye (1968) produced a map and report on the geology of the Crescent Lake area or the central part of the current study area. More recently, reports and maps produced by Sutcliffe (1986, 1988) and Berger (1992) describe the geology in adjacent areas.

Smyk et al. (2005) summarizes the current knowledge of mineralization and recent exploration activity within the study area. In addition to the Cu-Mo-Au-Ag-mineralized porphyry at Kilometre 61 mentioned above, there is potential for Au and Cu-Ni-PGE mineralization in the area (Smyk et al. 2005). Pye (1968) describes some of the historic prospecting activity along the Caribou Lake greenstone belt and discusses occurrences of Cu, Au, Fe, Li, Mo, Ni, Zn and Fe-sulphides. As well, Breaks, Selway and Tindle (2002) discuss the geology and mineral potential of fertile and peraluminous granites and related rare-element pegmatites that occur within the Caribou Lake greenstone belt.

Very few investigations of the surficial geology of the study area have been undertaken. Pioneering work by Zoltai (1965a, 1965b) describes the distribution and origin of the dominant landforms in the area. Northern Ontario Engineering Geology Terrain Study (NOEGTS) maps at a scale of 1:100 000 and reports (Cooper 1983a, 1983b; McQuay 1983a, 1983b; OGS–MNR 2005) describe the distribution of surficial materials, landforms, relief and drainage conditions within the study area.

PROJECT STATUS

During August 2005, a reconnaissance-level evaluation of the project area was carried out to determine the potential for using drift (till) prospecting to aid in mineral exploration of the area and to determine directions of glacial transport. E.G. Pye (1968, p.40) wrote, "Because of the general scarcity of outcrops throughout much of the map-area, conventional prospecting is difficult." Till, however, is generally well distributed in the study area and is commonly thick enough to obtain C-horizon samples. There are, however, a few areas of thick glaciofluvial and glaciolacustrine sediments within the study area that hinder the collection of till samples. However, these are commonly located over the area of granitic and granodioritic rocks located south of the Caribou Lake greenstone belt. The overall pattern of ice advance as recorded by glacial striae is displayed in Figure 20.2. Multiple directions of ice flow (striae) were recorded at only a few localities: commonly located near (up-ice flow) of former ice marginal positions such as the Nipigon moraine.

Till was sampled for heavy-mineral concentrate (HMC) analysis at 42 sites and samples have been sent to Overburden Drilling Management Ltd., Nepean, Ontario, for processing. C-horizon till matrix samples were collected at 80 sites for geochemical analysis by the Ontario Geoscience Laboratories (GeoLabs) at the Ministry of Northern Development and Mines (*see* Figure 20.2). Pebbles were also collected at the till matrix sample sites for lithology identification to provide information on distance of glacial transport. Sampling was extended eastward from the study area along and beyond the Caribou Lake greenstone belt because of the availability of recently constructed forest access roads. Prior to beginning this field work, several weeks were spent collecting ground truth in the area immediately south of Lake Nipigon. This work is leading to the creation of a regional surficial geology map covering the area encompassed by the recent Lake Nipigon Region Geoscience Initiative (LNRGI).

It is planned to continue this project next summer. Work will include collecting additional samples to improve the distribution and the density of sample locations. Additional information will be collected to refine the record of ice movement and field mapping the distribution of surficial sediments will be undertaken to better understand the behaviour of the Laurentide Ice Sheet as it relates to glacial dispersal of mineralized bedrock.

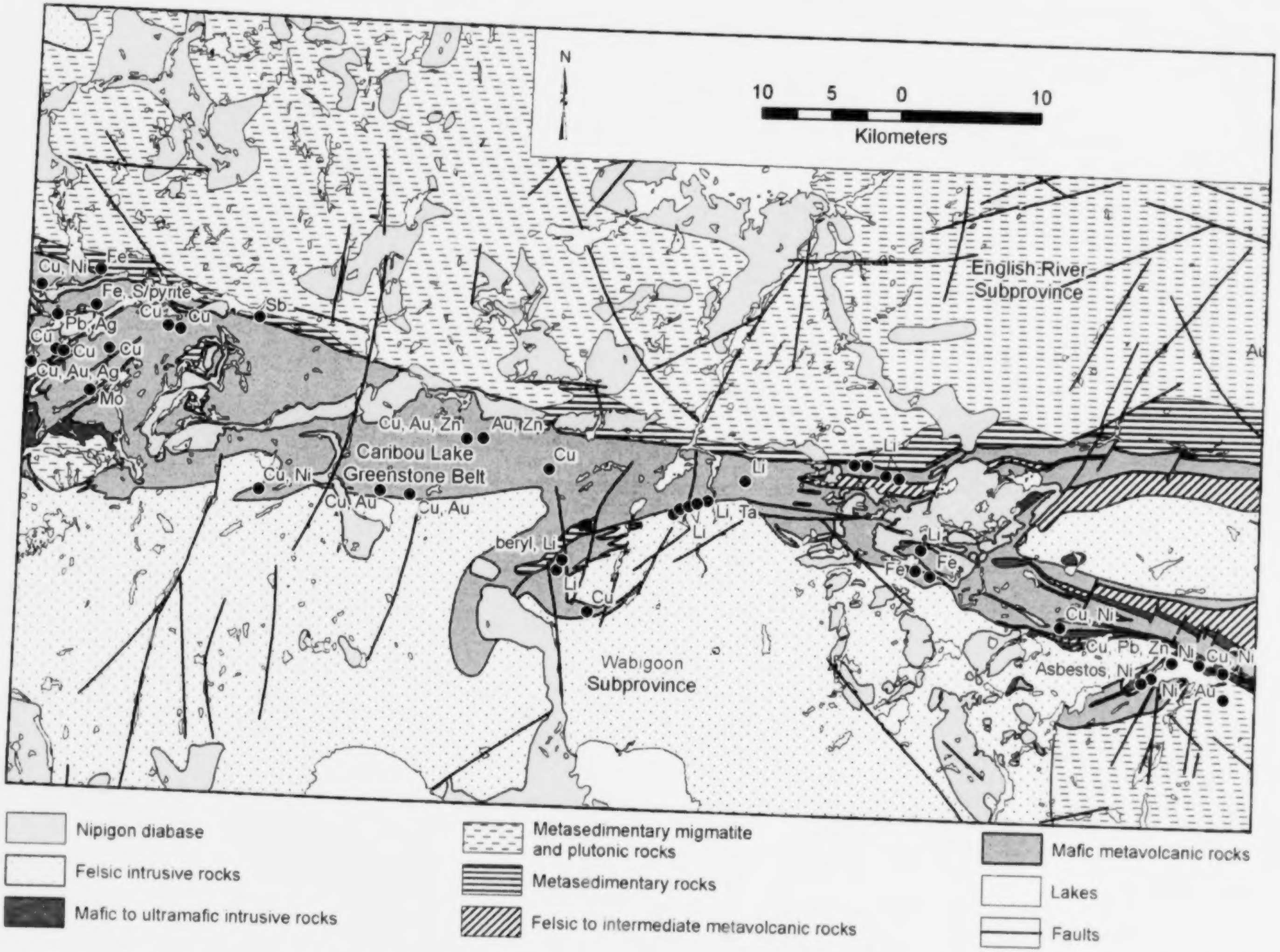

N
10 5 0 10
Kilometers
English River Subprovince
Wabigoon Subprovince
Caribou Lake Greenstone Belt
Cu, Ni
Fe
Fe, S/pyrite
Pb, Ag
Cu
Cu, Au, Ag
Mo
Sb
Cu, Au, Zn
Au, Zn
Cu, Ni
Cu, Au
Cu, Au
Cu
Li
Li, Ta
beryl, Li
Fe
Cu, Pb, Zn
Asbestos, Ni
Ni
Au
Nipigon diabase
Felsic intrusive rocks
Mafic to ultramafic intrusive rocks
Metasedimentary migmatite and plutonic rocks
Metasedimentary rocks
Felsic to intermediate metavolcanic rocks
Mafic metavolcanic rocks
Lakes
Faults

Figure 20.1. Generalized bedrock geology (*after* Percival et al. 2002; Stott et al. 2002) and mineral occurrences of the study area. Mineral occurrences (black dots) are from the Mineral Deposits Inventory (MDI) and current to 2004 (OGS 2004).

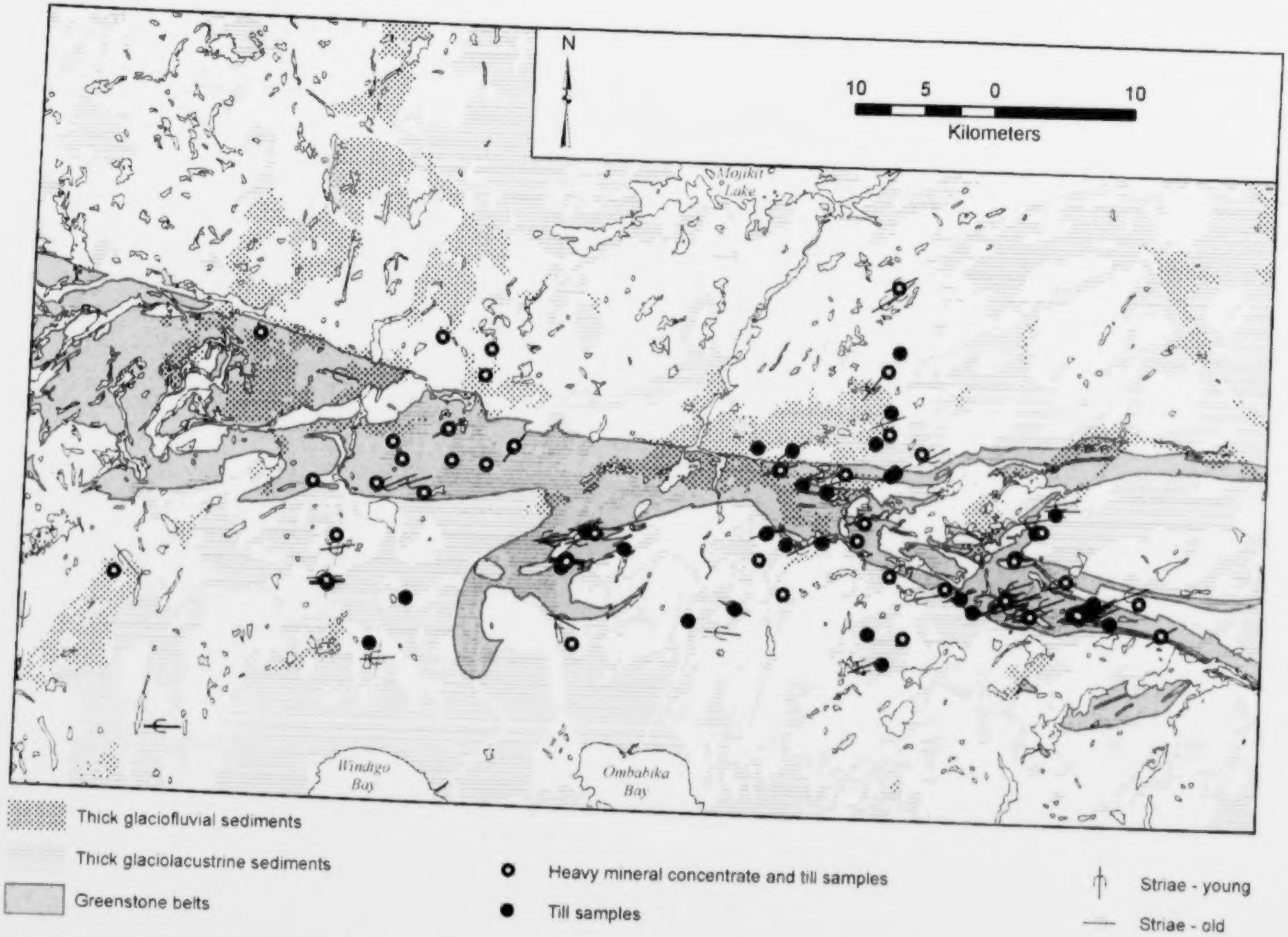

N
10 5 0 10
Kilometers
Mojikit Lake
Windigo Bay
Ombabika Bay
Thick glaciofluvial sediments
Thick glaciolacustrine sediments
Greenstone belts
Heavy mineral concentrate and till samples
Till samples
Striae - young
Striae - old

Figure 20.2. Location of till samples collected for HMC and geochemical analysis and areas of extensive cover of non-till sediments (*modified from* OGS–MNR, 2005). Location of greenstone belts *modified from* Percival et al. 2002 and Stott et al. 2002.

REFERENCES

Berger, B.R. 1992. Geology of the Toronto Lake area, District of Thunder Bay; Ontario Geological Survey, Open File Report 5784, 145p.

Breaks, F.W., Selway, J.B. and Tindle, A.G. 2002. Fertile and peraluminous granites and related rare-element pegmatite mineralization, Superior Province, northeastern Ontario; *in* Summary of Field Work and Other Activities, Ontario Geological Survey, Open File Report 6100, p.6-1 to 6-42.

Cooper, A.J. 1983a. Whitewater Lake area (NTS 52-I/NW), District of Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 7, 17p.

——— 1983b. Mojikit Lake area (NTS 52-I/NE), District of Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 8, 20p.

McQuay, D.F. 1983a. Armstrong area (NTS 52-I/SW), District of Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 16, 24p.

——— 1983b. Windigo Bay area (NTS 52-I/SE), District of Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 17, 18p.

Ontario Geological Survey, 2004. Mineral Deposit Inventory Version 2 (MDI2), October 2004 Release; Ontario Geological Survey.

Ontario Geological Survey, Ministry of Northern Development and Mines, and Northeast Science and Information Section, Ministry of Natural Resources 2005. Digital Northern Ontario Engineering Terrain Study (NOEGTS); Ontario Geological Survey, Miscellaneous Release—Data 160.

Percival, J.A., Whalen, J.B., Tomlinson, K.Y., McNicoll, V. and Stott, G.M. 2002. Geology and tectonostratigraphic assemblages, north central Wabigoon Subprovince, Ontario; Ontario Geological Survey, Preliminary Map P.3447, or Geological Survey of Canada, Open File 4270, scale 1:250 000.

Pye, E.G. 1968. Geology of the Cresent Lake area, District of Thunder Bay; Ontario Department of Mines, Geological Report 55, 72p.

Smyk, M.C., White, G.D., Magee, M.A. and Komar, C. 2005. Report of Activities, 2004, Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District; Ontario Geological Survey, Open File Report 6147, 37p.

Stott, G.M., Davis, D.W., Parker, J.R., Straub, K.J. and Tomlinson, K.Y. 2002. Geology and tectonostratigraphic assemblages, eastern Wabigoon Subprovince, Ontario; Ontario Geological Survey, Preliminary Map P.3449, or Geological Survey of Canada, Open File 4285, scale 1:250 000.

Sutcliffe, R.H. 1986. Geology of the Funger Lake area, District of Thunder Bay; Ontario Geological Survey, Report 247, 58p.

——— 1988. Geology of the Fletcher Lake area, District of Thunder Bay; Ontario Geological Survey, Report 251, 65p.

Zoltai, S.C. 1965a. Glacial features of the Quetico–Nipigon area, Ontario; Canadian Journal of Earth Sciences, v.2, p.247-269.

——— 1965b. Surficial geology, Thunder Bay; Ontario Department of Lands and Forests, Map S265, scale 1:506 880.

21. Project Unit 05-017. Regional Modern Alluvium Sampling Survey of the Gogama–Shining Tree Region, Northeastern Ontario

V.E. Felix[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The recent discovery of diamond-bearing kimberlite pipes and other rocks (i.e., lamprophyres) thought to have potential to host diamonds in the Kirkland Lake–New Liskeard–Temagami area of northeastern Ontario has triggered an increase in diamond exploration activity within the region. Several of the pipes occur in clusters and align with the north-northwest-trending Lake Timiskaming Structural Zone (LTSZ), and locally with conjugate structures to the LTSZ (Sage 1996, 2000). Many additional unidentified kimberlites likely occur along the LTSZ (Sage 2000) and this suggestion has contributed to increased exploration activity along this corridor.

BACKGROUND AND CURRENT STUDY

Kimberlite is a rock type commonly recognized as the primary host for diamond. The suite of kimberlite indicator minerals is known to include pyrope and eclogitic garnets, magnesium ilmenite, chromite, chrome diopside, forsteritic olivine and diamond. The presence of these indicator minerals in modern alluvium samples can be used to determine the prospect for and proximity of any diamond-bearing kimberlites in an area. As well, other heavy mineral assemblages including gold grains and metamorphic or magmatic massive sulphide indicator minerals (MMSIM®[1]) may be recovered from collected samples and utilized to assess the mineral potential of a region.

The location of diamond-bearing kimberlite is controlled by several important factors that should be considered in exploration. On a regional scale, structural association, for example, bedrock fractures and faults appear to control final emplacement of kimberlite. The northwest-trending Lake Timiskaming Structural Zone, a deep-crustal fault zone, is the host of a number of kimberlite pipes. Kimberlite clusters occur along this regional trend at Attawapiskat, Coral Rapids, Matheson, Kirkland Lake, Timiskaming, Cobalt, Picton and Syracuse in New York State (Sage 1996).

To further evaluate the diamond and other mineral potential along this regional trend, the Ontario Geological Survey has recently completed a series of modern alluvium surveys along the Mattawa to Timmins corridor of northeastern Ontario. These include 1) the Temagami–Marten River area (Allan 2001); 2) the Mattawa–Cobalt Corridor (Reid 2002); 3) the Cobalt–Elk Lake area (Reid 2004) and 4) the Kirkland Lake–Matachewan Region (Reid 2003). The current study, covering the Gogama–Shining Tree area is a western extension of the survey completed in 2003 (Figure 21.1). The primary objective of the

---

[1]MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.21-1 to 21-7.

© Queen's Printer for Ontario, 2005

study is to extend the regional information base concerning the types and distribution of kimberlite indicator minerals (KIMs) found in modern alluvium northwestward to the Timmins area.

A till sampling survey previously carried out within the Peterlong Lake area revealed a spatial pattern of kimberlite indicator mineral occurrences suggesting a local source for kimberlite indicator mineral grains (Bajc and Crabtree 2001). Linear clusters of samples containing indicator minerals were revealed by the till sampling survey and proposed to be associated with structural features present within the study area (Bajc and Crabtree 2001). Results from the current modern alluvium survey will be used to build upon the indicator mineral data generated by previous work and in addition, add to the overall heavy mineral indicator database for the region.

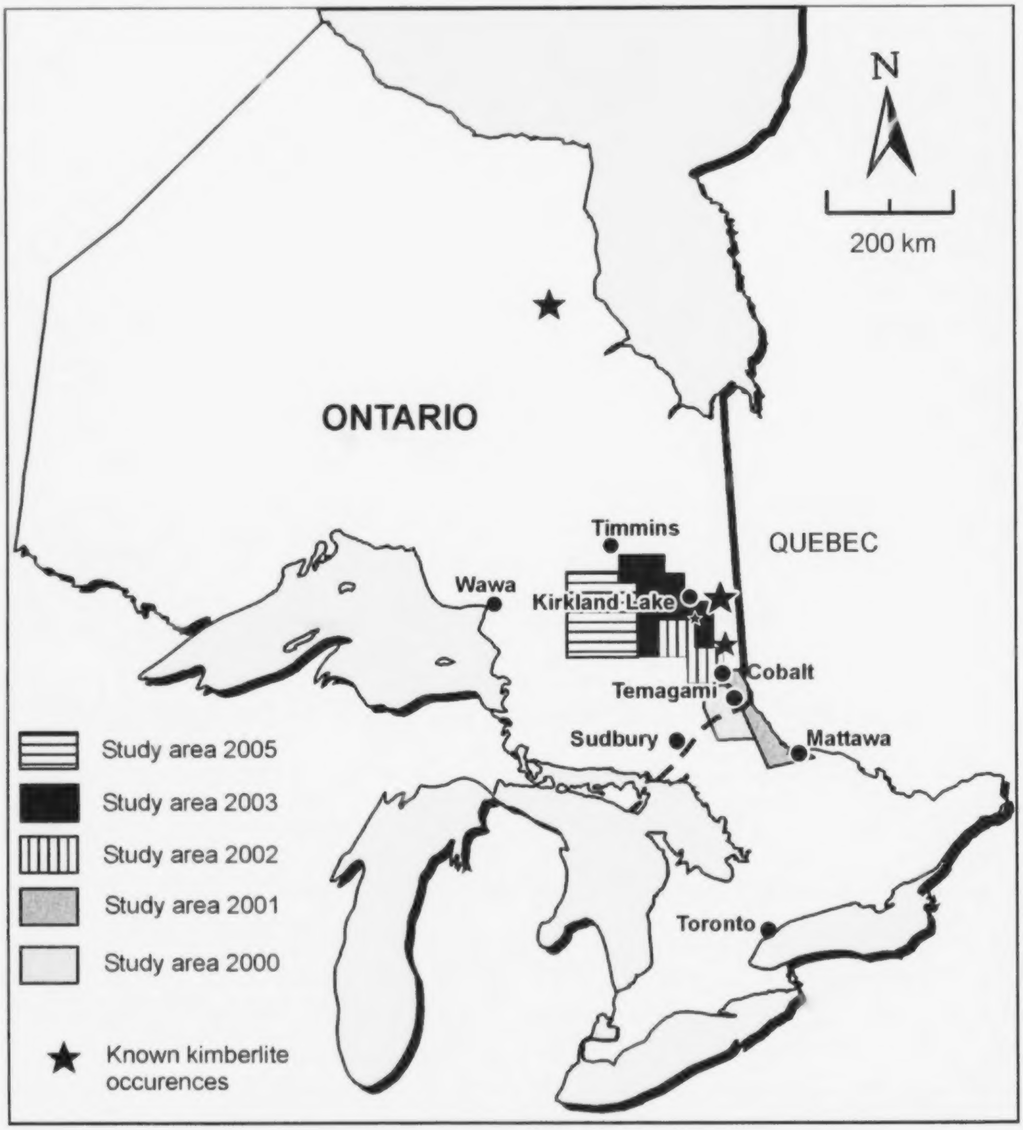

N
200 km
ONTARIO
QUEBEC
Timmins
Wawa
Kirkland Lake
Cobalt
Temagami
Sudbury
Mattawa
Toronto
Study area 2005
Study area 2003
Study area 2002
Study area 2001
Study area 2000
Known kimberlite occurences

Figure 21.1. Location of the 2005 study area in relation to previous study areas. Dashed line approximates the Grenville Front.

The Gogama–Shining Tree study area is represented on the following 1:50 000 scale National Topographic System (NTS) map sheets: 42 A/4 (Kenogaming Lake), 42 A/3 (Peterlong Lake), 41 P/13 (Mattagami Lake), 41 P/14 (Sinclair Lake), 41 P/12 (Gogama), 41 P/11 (Shining Tree) and the west part of 41 P/10 (Gowganda) and 41 P/15 (Matachewan).

PHYSIOGRAPHY

The study area lies within with Abitibi Uplands physiographic region (Bostock 1970). These uplands are underlain by crystalline Archean rocks and characterized by broad rolling surfaces that rise gently from the Hudson Bay Lowland in the north, reaching about 500 m asl near their southwest and southern extent. Most of the uplands lie between 300 and 400 m asl in elevation. These uplands form a rocky landscape, scattered with lakes and large areas that are mantled by a variety of glacial deposits (Thurston 1991).

Elevations in the Gogama–Shining Tree area range from a low of less than 335 m near Shining Tree to a high of 547 m in Stetham Township, northeast of Gogama. The Sinclair Lake map area, located north of Shining Tree is generally a low relief lowland area with elevation and local relief increasing gradually to the south. Relief in the Peterlong Lake area is also characterized as low. Fine-grained glaciolacustrine deposits in McArthur, Douglas and Fallon townships have produced a relatively flat, poorly drained area with relief generally less than 30 m. Low relief is typical over parts of the study area covered by glaciofluvial and eolian deposits and moderate relief is prevalent in those areas covered by morainal and bedrock-dominated terrain (Roed and Hallett 1979).

The Great Lakes–Hudson Bay drainage divide runs northward through the Shining Tree map sheet and the southeast corner of the Sinclair Lake map sheet. Western parts of the Shining Tree and Sinclair Lake map sheets are drained by the northward flowing Mattagami River. Central and eastern parts of the Sinclair Lake map area are drained by the Grassy River which also flows north. The southward flowing West Montreal River drains the central and eastern portions of the Shining Tree map sheet.

BEDROCK GEOLOGY

The Gogama–Shining Tree survey area lies within the western Abitibi Subprovince, a granite-greenstone terrane of the Superior Province. The western half of the survey area is dominated by the Kenogamissi Batholith (Figure 21.2). This Archean (2.75–2.65 Ga) granitoid complex marks the western limit of the Abitibi greenstone belt (Jackson and Fyon 1991) and separates the Abitibi greenstone belt from the Swayze greenstone belt. Compositionally, the batholith is granitic, quartz-syenitic or quartz-monzonitic and contains biotite as the main mafic mineral (Machado 2002).

The Abitibi greenstone belt displays a complex succession of volcanic, sedimentary and granitic rocks, which typically have undergone greenschist- to subgreenschist-facies metamorphism (Jolly 1978).

Supracrustal rocks in the Shining Tree area have been divided into the older (2750–2700 Ma) Pacaud, Deloro, Kidd–Munro and Tisdale assemblages and the younger 2687 Ma Timiskaming assemblage (Oliver et al. 1998). The Timiskaming assemblage unconformably overlies the older assemblages.

Rock units in the Sinclair Lake area include Keewatin-age metavolcanic rocks (ultramafic to felsic) and rocks of the Timiskaming assemblage. In the southeastern portion of this map area and western portion of the Peterlong Lake area, these rocks are unconformably overlain by sedimentary rocks of the

Huronian Supergroup. Huronian sedimentary rocks are composed of mature, well sorted conglomerate, quartz arenite, wacke and siltstone (Machado 2002). In Sothman, Kemp and Mond townships, Nipissing mafic rocks intrude both the Keewatin-age rocks and the Huronian Supergroup (Ayer et al. 2003). Numerous diabase dikes occur in this area and are intrusive into all other lithologies.

Archean supracrustal rocks in the Peterlong Lake area belong to the Bartlett, Peterlong, Bowman, Geikie and Watabeag assemblages and are dominated by metavolcanic lithologies (Jackson and Fyon 1991). Three compositional classes of metavolcanic rocks have been recognized. These include 1) a calc-alkalic suite; 2) a tholeiitic suite, which includes iron-rich and magnesium-rich end members; and 3) a komatiitic suite. The Geikie and Adams plutons, 2 similar stocks of granodiorite, intrude the supracrustal rocks. The granodiorites of these plutons are medium-grained, light grey-pink, massive to weakly foliated and generally porphyritic (Pyke 1978).

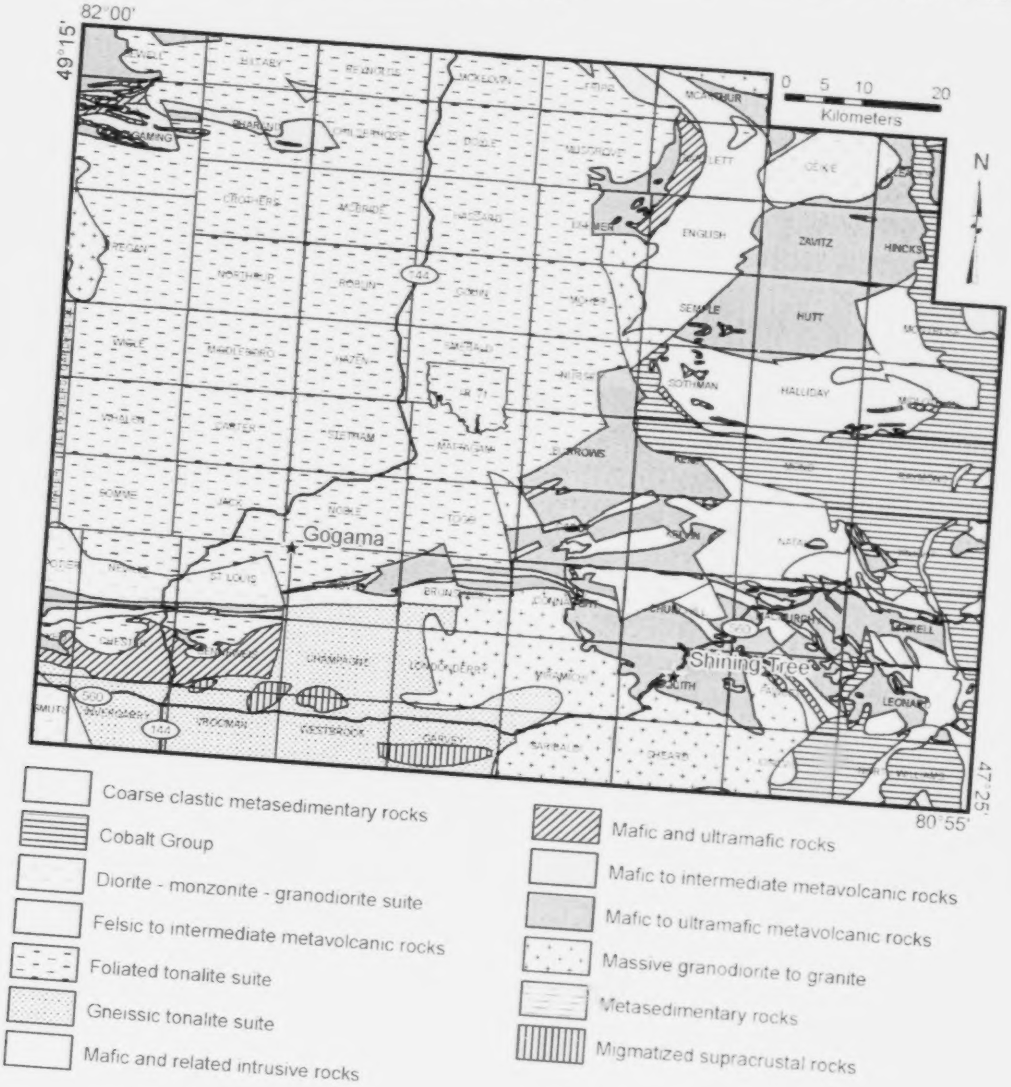

82°00'
49°15'
0 5 10 20
Kilometers
N
MCARTHUR
GEIKIE
ENGLISH
ZAVITZ
HINCKS
SEMPLE
HUTT
SOTHMAN
HALLIDAY
KEMP
144
Gogama
Shining Tree
LEONARD
560
144
47°25'
80°55'
Coarse clastic metasedimentary rocks
Cobalt Group
Diorite - monzonite - granodiorite suite
Felsic to intermediate metavolcanic rocks
Foliated tonalite suite
Gneissic tonalite suite
Mafic and related intrusive rocks
Mafic and ultramafic rocks
Mafic to intermediate metavolcanic rocks
Mafic to ultramafic metavolcanic rocks
Massive granodiorite to granite
Metasedimentary rocks
Migmatized supracrustal rocks

Figure 21.2. Regional bedrock geology of the study area.

Huronian Supergroup. Huronian sedimentary rocks are composed of mature, well sorted conglomerate, quartz arenite, wacke and siltstone (Machado 2002). In Sothman, Kemp and Mond townships, Nipissing mafic rocks intrude both the Keewatin-age rocks and the Huronian Supergroup (Ayer et al. 2003). Numerous diabase dikes occur in this area and are intrusive into all other lithologies.

Archean supracrustal rocks in the Peterlong Lake area belong to the Bartlett, Peterlong, Bowman, Geikie and Watabeag assemblages and are dominated by metavolcanic lithologies (Jackson and Fyon 1991). Three compositional classes of metavolcanic rocks have been recognized. These include 1) a calc-alkalic suite; 2) a tholeiitic suite, which includes iron-rich and magnesium-rich end members; and 3) a komatiitic suite. The Geikie and Adams plutons, 2 similar stocks of granodiorite, intrude the supracrustal rocks. The granodiorites of these plutons are medium-grained, light grey-pink, massive to weakly foliated and generally porphyritic (Pyke 1978).

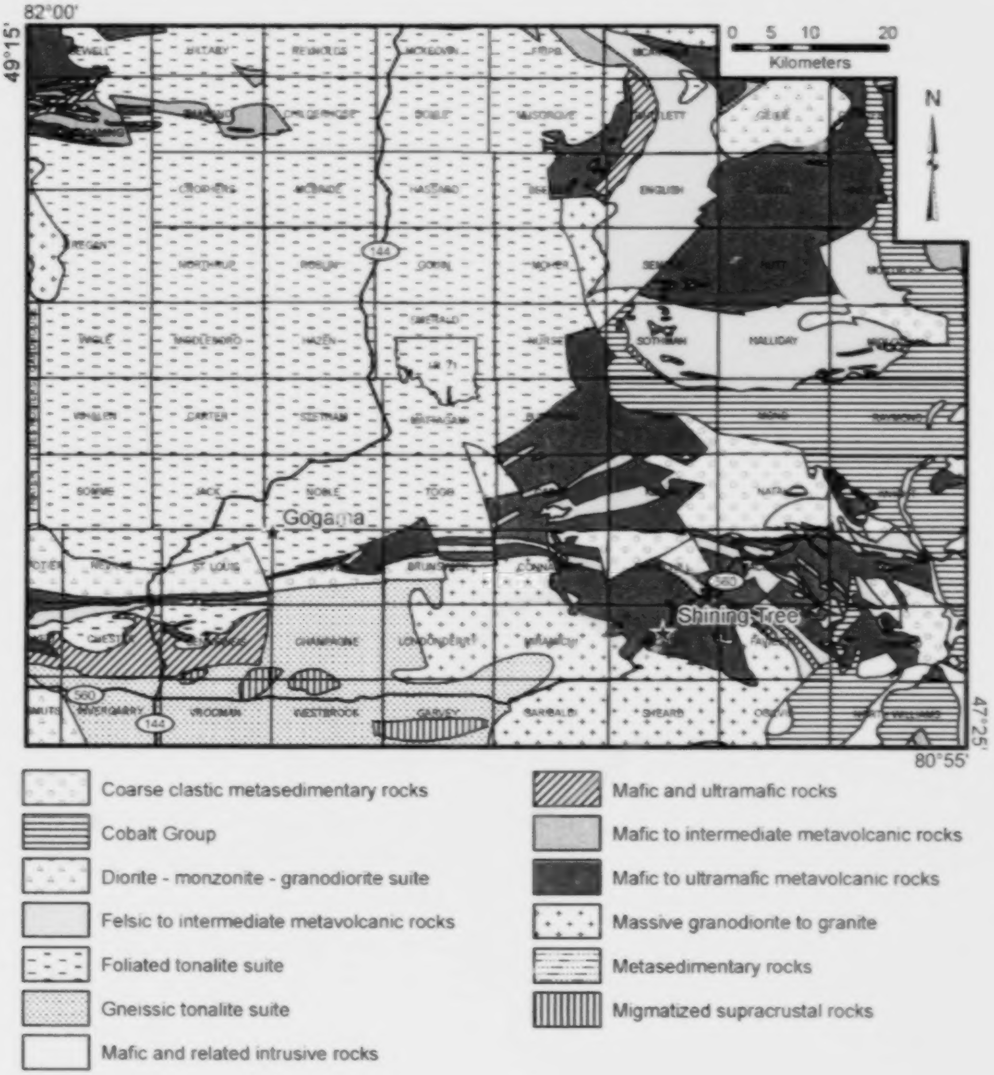

82°00'
49°15'
0 5 10 20
Kilometers
N
144
Gogama
560
Shining Tree
47°25'
80°55'
Coarse clastic metasedimentary rocks
Cobalt Group
Diorite - monzonite - granodiorite suite
Felsic to intermediate metavolcanic rocks
Foliated tonalite suite
Gneissic tonalite suite
Mafic and related intrusive rocks
Mafic and ultramafic rocks
Mafic to intermediate metavolcanic rocks
Mafic to ultramafic metavolcanic rocks
Massive granodiorite to granite
Metasedimentary rocks
Migmatized supracrustal rocks

Figure 21.2. Regional bedrock geology of the study area.

Faults and joints in the bedrock are numerous and the presence of many faults is evident in the terrain. Northwest-trending fault systems are prominent in the study area and are correlated with the Lake Timiskaming rift system.

QUATERNARY GEOLOGY

During the Wisconsin Episode, the study area was covered by glacial ice of the Laurentide Ice Sheet (Roed and Hallett 1979). By approximately 11 000 years ago, the ice margin had receded to the Gogama area and a halt in the recession of ice is marked by the position of the Sultan Scarp. This morainal scarp is a significant deposit as it is recognized as the only major still stand of the ice sheet in the project area (Roed and Hallett 1979). This prominent 55 m high scarp forms part of the height of land that separates the Great Lakes and Hudson Bay watersheds (Bernier and Goff 1993).

The distribution of surficial deposits in the area is strongly controlled by topography with till predominating at the highest elevations, glaciofluvial ice-contact and outwash deposits in valleys and glaciolacustrine and organic deposits in topographic lows (Alcock 1991).

Most upland regions within the study area are characterized by bare bedrock or a thin (generally less than 1 m) discontinuous cover of till. Isolated, thicker deposits of till occur on the larger upland surfaces, in the lee of bedrock highs and in low areas between bedrock knobs (Alcock 1991). Till was deposited primarily by lodgement and/or meltout processes or as ice-marginal debris flow and is typically stony, silty to sandy with low matrix carbonate (Bajc and Crabtree 2001).

Ice-contact stratified drift deposits occur in eskers, kames, subaqueous fans, crevasse fillings and stagnant ice features (Alcock 1991). Several esker complexes are located in the survey area. The eskers occur as southward-trending hummocky to rolling ridges of sand and gravel flanked by gently rolling outwash plains (Roed and Hallett 1979).

Detailed 1:50 000 scale Quaternary geology maps are available for the Shining Tree and Sinclair Lake map sheets (Alcock 1991) and the Peterlong Lake map sheet (Bajc and Paterson 2000). Engineering geology terrain maps have been produced for the area at a scale of 1:100 000 (Roed and Hallett 1979).

REGIONAL SAMPLING SURVEY

The current regional modern alluvium survey, covering an area of approximately 6500 km^2, was conducted in June, July and August 2005. A total of 328 modern alluvium samples and 9 till samples were collected. Access to the study area was achieved by a network of primary and secondary roads, logging roads and all-terrain vehicle (ATV) trails. The presence of numerous lakes and rivers provided boat access to otherwise remote locations.

Sample site selection was based on several criteria: 1) preference to larger, high order (high energy) streams/rivers; 2) maximizing the length of stream/river upstream of sample site location; 3) avoidance of potential anthropogenic influences by sampling at least 50 m upstream from road or rail bridges, etc.; 4) obtaining a uniform sample density and 5) sampling all major drainage catchments.

The resulting distribution of collected samples provides excellent regional coverage. Regional overburden heavy mineral surveys provide data on the types, distribution and relative concentration of heavy minerals in a given region. Sample site locations were accurately recorded using a global positioning system (GPS). Real-time differential correction of GPS data was completed to provide the most accurate positioning possible.

Modern alluvium was chosen as the primary sampling media for this study as it provides a means of obtaining a fast, relatively inexpensive heavy mineral signature for individual drainage basins (Morris et al. 2000). Points of heavy mineral deposition within streams were targeted for sample collection. Sampling points included the deepest part of the channel; longitudinal and point bars; and boulder, log and vegetation traps. Material was sieved in the field using a 5 mm mesh screen and the finer size fraction (<5 mm) was retained. At all sites, a 2 to 3 kg sample of this material was collected for analysis of fine fraction geochemistry. A 15 to 20 kg sample of fine fraction (<5 mm) material was collected for heavy mineral concentration and subsequent gold grain determinations These samples were sent for heavy mineral processing to isolate and identify kimberlite and other indicator minerals. Following separation of the indicator minerals, electron microprobe analysis will be completed to determine the precise grain geochemistry.

Where possible, approximately 50 pebbles were collected from the coarser (>5 mm) fraction at each sample site for pebble lithology classification. Pebble lithologies classified to date indicate that, typically, stream deposits are locally derived. In addition, at most sites, a small portion of the stream sediment was panned and the resultant "fine-fraction" concentrate retained.

A number of sites had a high percentage of fine sand, silt or organic material and so were deemed inappropriate for indicator mineral sampling. At these locations, however, a sample was collected for fine fraction geochemistry.

At each sample location, a site description consisting of observations on 1) bedrock exposure and type; 2) presence of overburden and type; 3) surface expression; 4) drainage; 5) vegetation type; 6) material texture, 7) clast size, abundance, shape and type; 8) type of sample site and 9) anthropogenic factors.

Results from the study are expected to be released in early 2006.

REFERENCES

Allan, S.E. 2001. Regional modern alluvium sampling survey of the Temagami–Marten River area, northeastern Ontario; Ontario Geological Survey, Open File Report 6043, 194p.

Alcock, P.W. 1991. Quaternary geology of the Shining Tree area; Ontario Geological Survey, Open File Report 5810, 120p.

Ayer, J.A., Trowell, N.F., Josey, S., Nevills, M. and Valade, L. 2003. Geological compilation of the Matachewan area, Abitibi greenstone belt; Ontario Geological Survey, Preliminary Map P.3527, scale 1:100 000.

Bajc, A.F. and Crabtree, D.C. 2001. Results of regional till sampling for kimberlite and base metal indicator minerals, Peterlong Lake–Radisson Lake area, northeastern Ontario; Ontario Geological Survey, Open File Report 6060, 65p.

Bajc, A.F. and Paterson, J.T. 2000. Quaternary geology of the Peterlong lake area, northeastern Ontario; Ontario Geological Survey, Map 2611, scale 1:50 000.

Bernier, M.A. and Goff, J.R. 1993. Quaternary mapping and surface drift sampling program, western Swayze greenstone belt; *in* Summary of Field Work and Other Activities 1993; Ontario Geological Survey, Miscellaneous Paper 162, p.250-255.

Bostock, H.S. 1970. Physiographic subdivisions of Canada; *in* Geology and economic minerals of Canada, Geological Survey of Canada, Economic Report No. 1, p.10-30.

Jackson, S.L. and Fyon, J.A. 1991. The western Abitibi Subprovince in Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.405-482.

Jolly, W.T. 1978. Metamorphic history of the Archean Abitibi belt; *in* Fraser J.A. and Heywood W.W. (eds.), Metamorphism in the Canadian Shield; Geological Survey of Canada, Paper 78-10, p.63-78.

Machado, G. 2002. Geology of Burrows, Kemp and Mond townships, Shining Tree area; Ontario Geological Survey, Open File Report 6077, 41p.

Morris, T.F., Sage, R.P., Crabtree, D.C. and Pitre, S.A. 2000. Kimberlite, base metal, gold and carbonatite exploration targets, derived from overburden heavy mineral data, Killala Lake area, northwestern Ontario; Ontario Geological Survey, Open File Report 6013, 114p.

Oliver, H.S., Hughes, D.J., Hall, R.P. and Johns, G.W. 2000. Lithogeochemistry of the Shining Tree area; *in* Summary of Field Work and Other Activities 2000; Ontario Geological Survey, Open File Report 6032, p.6-1 to 6-14.

Pyke, D.R. 1978. Geology of the Peterlong Lake area, Districts of Timiskaming and Sudbury; Ontario Geological Survey, Report 171, 53p.

Reid, J.L. 2002. Regional modern alluvium sampling survey of the Mattawa–Cobalt corridor, northeastern Ontario; Ontario Geological Survey, Open File Report 6088, 235p.

——— 2003. Regional modern alluvium sampling survey of the Kirkland Lake–Matachewan Region, northeastern Ontario; *in* Summary of Field Work and Other Activities 2003; Ontario Geological Survey, Open File Report 6120, p.19-1 to 19-9.

——— 2004. Regional modern alluvium sampling survey of the Cobalt–Elk Lake area, northeastern Ontario; Ontario Geological Survey, Open File Report 6119, 140p.

Roed, M.A. and Hallett, D.R. 1979. Gogama area (NTS 41P/NW), districts of Sudbury and Timiskaming; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 82, 17p. Accompanied by Map 5019, scale 1:100 000.

Sage, R.P. 1996. Kimberlites of the Lake Timiskaming Structural Zone; Ontario Geological Survey, Open File Report 5937, 435p.

——— 2000. Kimberlites of the Lake Timiskaming structural zone: supplement; Ontario Geological Survey, Open File Report 6018, 123p.

Thurston, P.C. 1991. Geology of Ontario: Introduction; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.3-25.

22. Aggregate Resources Inventory Mapping in Ontario: A GIS-based Approach

C. Gao[1], F.R. Brunton[1], J. Shirota[1] and S. van Haaften[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The aggregate resources inventory mapping program was initiated in the late 1970s following the recommendations by the Ontario Mineral Aggregate Working Party (1977). The resultant Aggregate Resources Inventory Paper (ARIP) publications contain an assessment of both sand and gravel and bedrock-derived aggregate that constitute the major raw material for road-building and construction industries across the province. The ARIPs are important components in municipal land-use planning and resource management processes to ensure that adequate resources of mineral aggregate remain available for future use. Among the more than 170 published aggregate reports and accompanying maps, most cover the townships and counties within southern Ontario, a response to the population density and high resource demands in this region (Figure 22.1). With the rapid development and ever growing demand for mineral aggregate in areas such as the Greater Toronto Area (GTA), it is important to have high-quality aggregate maps so that balanced land-use plans can be developed to make the best use of available resources.

Although the geological approach and resource selection criteria remain unchanged (Cowan 1978; Kelly and Rowell 1995; Rowell and Gao 2000; Baker 2003), the Ontario Geological Survey (OGS) has recently adopted geographical information systems (GIS) technology in its aggregate mapping program. Methodologies for sand and gravel mapping and bedrock surface and overburden thickness determination have been developed since 2003 (van Haaften et al. 2004; Gao 2005; Gao et al. 2005; Gao 2005, ARIP 178, in progress; Ontario Geological Survey and Golder Associates, ARIP 165–Revised, in progress). As a result, future ARIPs will contain hard-copy reports and maps, but also attributed GIS maps for easy data access and manipulation. This paper provides an overview of these recent advances that OGS has made in aggregate mapping.

ASSESSMENT OF SAND AND GRAVEL RESOURCES

The resource inventory maps delineate and classify the surface and near-surface sand and gravel deposits based on their levels of resource significance, that is, primary, secondary and tertiary. Sand and gravel resource areas of primary significance are areas where a major resource is known to exist and should be considered as part of the aggregate supply for the area. Although deposits of secondary significance may not be considered to be the "best" resources in the study area, they may contain substantial amounts of resources and are considered as part of the aggregate supply for the area. Tertiary deposits are not considered to be important resource areas due to the low available resources or because of possible serious constraints related to extraction.

The Ontario Geological Survey has undertaken, as a GIS-based pilot project, an aggregate resources assessment study for the District Municipality of Muskoka, southern Ontario (Gao 2005, ARIP 178, in

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.22-1 to 22-11.

© Queen's Printer for Ontario, 2005

progress). Three major components of data sources, map layers and attributes, and the technical approach to the project are briefly described below.

Data

Multiple data sets are used in the construction of an ARIP, including field observations, geological maps, previously published reports, aerial photographs, water wells, oil and gas boreholes, and the historical records of sand and gravel pits archived by the Ontario Ministry of Transportation (MTO). Most of the data are explained in detail in the published ARIPs (e.g., Ontario Geological Survey 2004). The basic information on lakes and rivers and infrastructure such as roads and railways, are from MNR Natural Resources and Values Information System (NRVIS).

Of particular importance is the recently released GIS map of the Surficial Geology of Southern Ontario (Ontario Geological Survey 2003). It provides the platform for sand and gravel resource assessment in southern Ontario. This GIS product contains, under each deposit polygon, attributes of materials, such as sand, gravel or till, that can be quickly selected and exported to produce a sand and gravel map for the study area. The subsequent aggregate compilation is based on this map.

The data recorded prior to the year 2000 in MTO archives are scanned raster images stored on CDs. As a result, the index topographic map can be geo-referenced or "rubber-sheeted" and displayed as a GIS information layer that can be used in conjunction with Landsat images and shaded surface relief to rectify dislocated pits.

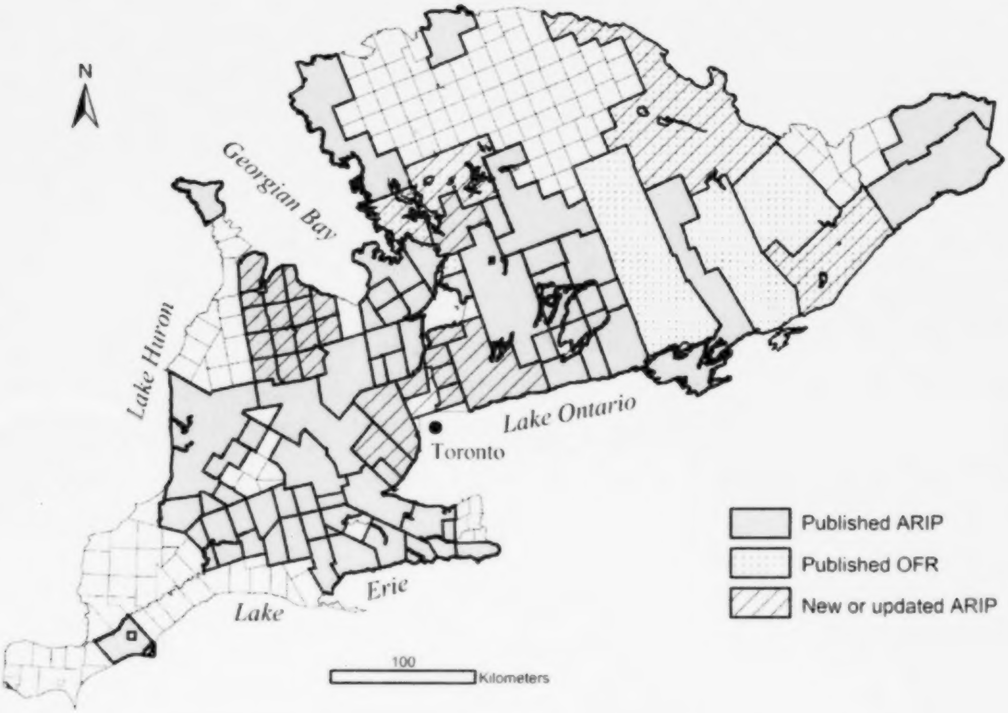


Figure 22.1. Aggregate resources inventory publications and municipal regions currently undergoing aggregate updating, southern Ontario.

Table 22.1. Selected map layers and attributes for a GIS aggregate map*.

Map Layers	Attributes	Description
SandGravel		Sand and gravel polygons attributed with thickness (m), extracted areas (ha), culture setbacks (ha), serial numbers given to selected primary areas and other features (see left)
	Label	Polygons are labelled with character strings e.g., G2-OW-O.D, indicative of an outwash deposit (OW) with >35% gravel (G), 3 to 6 m thickness (2), containing oversized clasts (O) and objectionable deleterious rocks (D)
	Rank	Polygons are coded with 1, 2 or 3, indicating primary, secondary or tertiary significance
	Tonnage_I	Tonnage for each of the polygonal areas (x10^6 tonnes)
	Tonnage_II	Tonnage after cutting off depleted and cultural setback (x10^6 tonnes)
Township (*also see* Table 22.3)		Provides municipal boundaries as well as total resources for each township, including total areal extent (ha) and tonnage (x10^6 tonnes)
Pits		Two map layers created for licenced (polygons) and unlicenced pits (points), attributed with pit numbers, face heights (m) and estimated gravel content (%). Hyperlinked to pits are field photographs
Samples_SG		Aggregate quality testing data of sand and gravel samples collected during OGS field work. Grain-size gradation curves are hyperlinked
TestHoles		Test holes drilled or excavated during OGS field work, attributed with brief geological descriptions, e.g., "0.9 m sand/0.5 m gravel/1.5 m sand/"
WaterWells_SG		Selected water wells, attributed with material layers, e.g., 4S/21SG indicating 4 m of sand, underlain by 21 m sand and gravel on bedrock; 4S/21SG/ indicates not reaching bedrock

* Based on Gao (ARIP 178, in progress). The map layer names are for reference only.

The Landsat-7 orthorectified colour raster images can be downloaded from http://geogratis.cgdi.gc.ca (Mapping Service Branch 2003). The resolution is about 30 m in southern Ontario. The active or recently active pits that normally exceed this size can be clearly located on these satellite remote sensing images. The surface relief map is derived from digital elevation models (DEM) provided by Ontario Ministry of Natural Resources (MNR). This map provides clues to the landscape that are sometimes used to critique pit locations as well as delineate geological deposits such as large outwash sand plains and gravelly ridges.

Map Layers and Attributes

In line with the objectives set out for sand and gravel resources inventory mapping (Ontario Mineral Aggregate Working Party 1977; Baker 2003), certain map layers and attributes are established, including polygonal layers for classifying and ranking the sand and gravel deposits, and point layers for unlicenced pits, water wells and test holes. Highlighted in Table 22.1 are the key map layers and attributes for a GIS map.

Create a Sand and Gravel Resource Map Layer

The sand and gravel resource map layer (*SandGravel, see* Table 22.1) provides the essential information for an ARIP. For mapping in southern Ontario, the GIS map of the Surficial Geology of Southern has been used as an initial sand and gravel map. The technical approach for creating a shape file using ESRI® ArcMap® 8.3 is outlined below.

Firstly, create a preliminary map that only contains sand, gravel or sand and gravel deposits. Under the map of Surficial Geology of Southern Ontario, open the attribute table of SGU_Poly, retain *sand* and *gravel* and remove all other entries such as *diamicton, silt* and *clay* under *Single Primary Material*. Also remove any sand deposits designated as *floodplain* under *Single Primary Genesis*. These deposits are unavailable for extraction because of their environmental sensitivity.

Secondly, edit and attribute the polygons. This is the compilation process to generate the sand and gravel resource map layer using all the data available, including field observations, water wells, MTO archived records and quality testing data. At this stage, the initially created polygons are split, expanded or adjusted as necessary. In line with field observations, new polygons may be added. After this step, all the polygons on the layer are categorized, labelled and ranked in resource significance (*see* Table 22.1).

Thirdly, eliminate NTS map boundaries. Polygons that are separated by 1:50 000 NTS map boundaries are to be merged to eliminate the artificial faults that inherently exist in the Surficial Geology of Southern Ontario (Ontario Geological Survey 2003). This is because aggregate mapping is focused on regional municipalities, different from surficial geological mapping that is normally conducted in areas defined by NTS maps.

Next, trim off polygons in lakes. The geological polygons immediately adjacent to lakes in Surficial Geology of Southern Ontario extend into the lakes (Ontario Geological Survey 2003). These polygons need to be separated from lakes in order to get the meaningful areal extents. This is accomplished by unionizing the sand and gravel map layer with the NRVIS shape file of the lakes.

Deal with polygon fragmentation. Some polygons are fragmented, for example, by rivers flowing across them after the above *Union* process. Although this may not pose a serious problem, the selected areas should be inspected carefully. Small fragmentary areas derived from a selected polygon may be lowered in rank in resource importance.

Intersect the sand and gravel map layer with the NRVIS shape file of lower tier municipalities. After this process, polygons at township boundaries are bisected or trisected, and the sand and gravel resource can be evaluated within individual townships.

Update polygon areal extent. The shape-file polygons are not automatically updated in areal extent if they have undergone modification. It is, therefore, important that the polygons are updated in areal extent for resource quantity calculation.

Remove small polygons (<0.01 ha). Small polygons, such as those less than 0.01 ha in areal extent, have probably resulted from the aforementioned fragmentation. These areas, no more than 0.2 by 0.2 mm or smaller than a pencil point in size at 1:50 000 scale, are unrealistic in terms of regional geological mapping. As such, they are removed.

Finally, the total resource areal extent and tonnages are calculated for each township and appended as attributes to the shape file of lower tier municipalities (*Township, see* Table 22.1).

ASSESSMENT OF BEDROCK RESOURCES

The second key component of an ARIP is a bedrock resources map that delineates the bedrock units, overburden thickness and selected resource areas. Although selection criteria are equivalent to those used for sand and gravel deposits, selection of bedrock is restricted to a single level of significance. Because of the wide variations in rock lithology, no resource areas are selected for Precambrian bedrock areas. The discussion below is focused on southern Ontario where Paleozoic sedimentary rocks are dominant. Apart from crushed stone, shale resources for brick manufacturing are also studied in southern Ontario (Golder Associates and Rowell 1996).

Ontario Geological Survey has developed a protocol for determining the bedrock surface and overburden thickness using ESRI® ArcGIS® statistical analysis function of kriging. Evaluation of bedrock resources is based upon a full integration and analysis of multiple spatial geo-data sets including water well and geotechnical drilling records as well as geological observations (Gao et al. 2005; Ontario Geological Survey and Golder Associates, ARIP 165–Revised, in progress). As described below, the protocol comprises the following components: data acquisition, data preparation and standardization, bedrock surface kriging, overburden thickness calculation, field work, and selection of aggregate potential areas.

Data Acquisition

The data within a buffer zone of at least 1 km in width beyond the boundary of the study area is also included into the working data base. Data sources include water well records, geological maps, DEM, geotechnical boreholes, oil and gas drilling logs and other data from published and unpublished hydrogeology, groundwater and landfill site investigations, municipalities and academic institutions.

The Ontario Ministry of Environment (MOE) water wells contribute over 70% of the data points used for bedrock subsurface determination and they are the most important information source for this protocol. However, the data quality is inconsistent and the water wells frequently contain geo-referencing errors and inaccurate or erroneous geological terms. Quality assurance and quality control (QA/QC) is, therefore, critical and those that fail to pass the filtering process are excluded from kriging.

The data extracted from published geology maps include a) bedrock outcrops from bedrock geology maps; and b) vertices of bedrock and thin drift areas (<1 m overburden) and bedrock outcrops from surficial geology maps. These data are from direct field observations and, therefore, reliable geological information.

The OGS maintains a databank of geotechnical boreholes, assembled in 1970s from various geology, hydrology and engineering related projects, which covers the GTA and the immediate adjacent area. However, geo-referencing errors have been noticed, probably incorporated during the process of data entry. A QA/QC check must be undertaken to filter out the problematic data.

The oil and gas drilling records are compiled and maintained by MNR Petroleum Resources Centre at London, Ontario. Although mostly located in areas underlain by Paleozoic bedrock, this data, if available, provides reliable information on the bedrock geology for the study area.

Data Preparation and Standardization

DATA FILTERING

The water wells and geotechnical boreholes need to be filtered and standardized. The common problems with water wells are ambiguous UTM zones and datum, unreliable locations, re-drilled wells, layers without depth values, wells located inside lakes and surface elevations inconsistent with DEM values. Water wells with these problems are rejected from the working database.

Table 22.2. An example translation table based on Ontario Geological Survey and Golder Associates (in process)*.

Primary Material	Secondary Material	Tertiary Material	Code
Shale	Stones	Loose	R
Shale	Sandy	Layered	R
Limestone	Stones	Medium-grained	R
Limestone	Silt	Soft	R
Silt	Sandy	Dense	O
Sand	Silty	Cemented	O
Gravel	Clean	Loose	O
Clay	Silt	Porous	O
Boulders	Gravel	Layered	O

* Material classification is from MOE database

Each water well should be marked clearly with UTM zonation and datum. Those with North American Datum 1927 (NAD27) datum are converted to NAD83. Water wells lacking clear indication of UTM co-ordinates and datum are flagged and barred from kriging.

In the MOE database, water well records contain reliability code ranging from 1 to 9. For instance, codes 1 and 2 indicate error margins less than 3 m and 3 to 10 m, respectively. Code 9 indicates that the location error is impossible to estimate. Water wells coded with 6 or higher, that is, over 300 m in error, are rejected.

Previously dug or re-drilled water wells may be duplicates of existing records. As such, these wells are regarded unreliable and removed.

Some water well layers are not assigned depth values. Without depth constraint, they are 'floating' in the strata succession, causing incorrect allocation of bedrock surface. As such, water wells containing such layers are removed.

The recorded ground elevations for some water wells and geotechnical boreholes are inconsistent with the DEM values. A difference between the record and the DEM of ±10 m is arbitrarily used as the threshold for accepting or rejecting a record. Those with over ±10 m difference between well elevation and DEM elevation are regarded problematic and removed.

BEDROCK DETERMINATION

Manually assigning bedrock surface for each water well is time consuming and, sometimes, impractical due to the large number of water wells, often on the order of 10 000 in a report area. One solution is to use a translation table that contains the unique combinations of the water well layer materials. The combinations are coded with 'O' or 'R' for overburden or bedrock, respectively (Table 22.2). Each of the wells is then searched downwards by computer using a pre-determined algorithm.

Coding unique combinations relies on an assumption that the geological terms used by water well drillers indicate the same materials and correspond to the geological terms used by geologists. Although this is true for most of the descriptions such as sand, gravel and limestone (Table 22.2), some terms used by water well drillers have different implications. For instance, *sandstone* is frequently used for compact sandy clay till and *slate* for shale or layered clay. While Precambrian bedrock such as *granite* in a water well log may indicate boulders in areas underlain by Paleozoic bedrock, their intra-formational occurrence in limestone bedrock certainly indicates erroneous description. It is, therefore, important for geologists to critique water well records and, if necessary, code the individual layers of a problematic combination.

Once completed, the translation table is used to assign all the water well layers with either O or R. The computer then runs a query and bedrock is determined if two consecutive 'R's are encountered down a water well or a single 'R' ending the hole. Otherwise, a water well is regarded as being located in overburden and not reaching the bedrock.

DATA STANDARDIZATION

The ground surface elevations are DEM values. The bedrock subsurface elevations are calculated as DEM minus the depth to bedrock, and as DEM minus 1 m for vertices of thin-drift areas. Bedrock outcrops use the DEM as their surface elevations (Figure 22.2).

Bedrock Surface Kriging

An initial bedrock elevation surface is kriged from all known bedrock points. It is carefully inspected in plan and perspective views for evidence of problems in the data set. Once problematic water wells are removed, the bedrock elevation surface may be kriged again (*see* Figure 22.2).

Some overburden water wells go deeper than the interpolated surface, indicating a lower bedrock surface at these localities. To honour them, their depth is used as the least bedrock depth to adjust or 'push down' the surface (*see* Figure 22.2). Again, a QA/QC check is conducted to track problematic water wells and, if necessary, the bedrock surface is re-kriged.

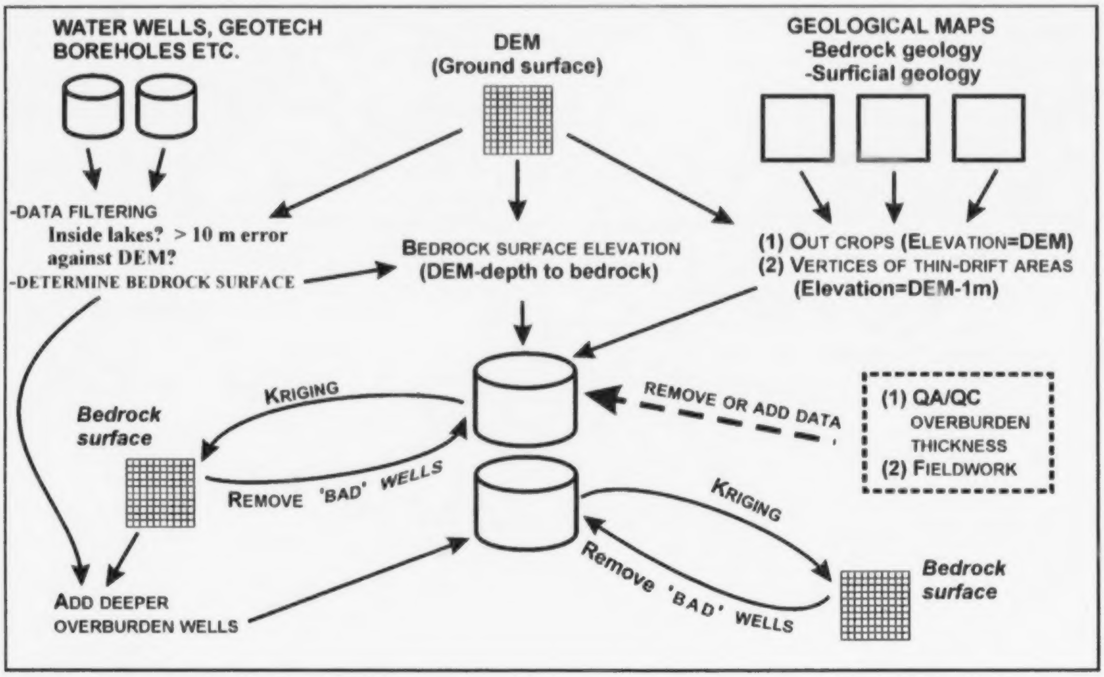

WATER WELLS, GEOTECH BOREHOLES ETC.
DEM (Ground surface)
GEOLOGICAL MAPS
-Bedrock geology
-Surficial geology
-DATA FILTERING
Inside lakes? > 10 m error against DEM?
-DETERMINE BEDROCK SURFACE
BEDROCK SURFACE ELEVATION (DEM-depth to bedrock)
(1) OUT CROPS (ELEVATION=DEM)
(2) VERTICES OF THIN-DRIFT AREAS (Elevation=DEM-1m)
KRIGING
Bedrock surface
REMOVE 'BAD' WELLS
REMOVE OR ADD DATA
(1) QA/QC OVERBURDEN THICKNESS
(2) FIELDWORK
KRIGING
Remove 'BAD' WELLS
Bedrock surface
ADD DEEPER OVERBURDEN WELLS

Figure 22.2. Flow chart outlining the key steps in bedrock surface determination. After each kriging, problematic or 'bad' water wells are removed and the surface is re-kriged. The QA/QC check on the overburden thickness map and subsequent field work removes or adds data to the data base and the whole kriging process is re-initiated.

Overburden Thickness Calculation

Overburden thickness is a simple subtraction between the kriged bedrock surface and DEM. However, negative values may arise from sudden depressions in the ground. It happens when a linear surface is interpolated or drawn between known data points across a steep escarpment or surface depression such as a river valley (Figure 22.3).

It is difficult, if not impossible, to collect enough data points along these areas to eliminate the negative values. On the other hand, an understanding of the landform and surficial geology of the study area is often helpful. Negative values arise in thin drift areas where rivers cut through the drift deposits. In thick overburden areas, this appears less likely to occur (*see* Figure 22.3). Steep escarpments, such as the Niagara Escarpment, experience intense erosion and normally contain a shallow cover of drift deposits. As such, the negative values may be reclassified as thin drift areas, for example, 0 to 1m. These areas may be verified during field investigations.

Quality control is critical at this stage. Aggregate mapping is focused on areas covered by less than 8 m of drift deposits. Water wells with incorrectly assigned bedrock change the outline and areal extent of map polygons depicting drift thickness, regardless of how large the overall database is. Key water well or borehole logs located within and nearby thin drift areas with potential for resource protection are subjected to scrutiny to ensure that the delineation is reasonable. The problematic water wells are marked and documented. They will be removed from the working database.

Field Work

Preliminary aggregate areas that are selected on the basis of the overburden thickness map and bedrock aggregate suitability are inspected and verified in the field. New data of outcrops and boreholes may be generated and some water wells found to be erroneous during field work. The working database is then updated and the whole process for bedrock surface determination and overburden thickness calculation is re-initiated for the final maps (*see* Figure 22.2).

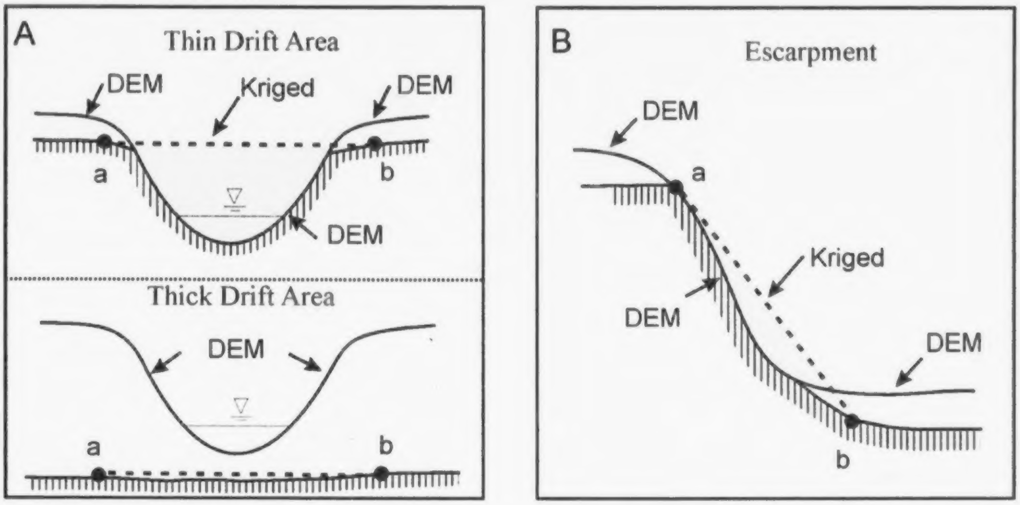


Figure 22.3. Schematic cross sections of areas where negative overburden thickness values (shaded area) typically arise after subtraction of a kriged bedrock surface from DEM or ground surface. Dashed line is the kriged linear surface between known bedrock data points *a* and *b*. A) Along a deep valley in an area covered by thin (top) and thick drift deposits (bottom). B) Along a steep cliff.

Table 22.3. Selected map layers of a bedrock GIS map.

Map Layers	Description
Bedrock	Selected thin drift areas (<8 m) underlain by aggregate-suitable bedrock units. Attributed with tonnages (x10^6 tonnes) for each polygon, tonnages after cutting off extracted and cultural setbacks, rock formations and brief geological descriptions.
Township (*also see* Table 22.1)	Municipal boundaries from MNR NRVIS database, attributed with total resources for each township, including total areal extent (ha) and tonnages (x10^6 tonnes) for crushed stone as well as shale resources.
DriftThickness	Overburden thickness categorized into 0–1 m, 1–8 m, 8–15 m and >15 m
Quarries	Two map layers created for licenced (polygons) and unlicenced quarries (points), attributed with quarry numbers, face heights (m) and remarks. Hyperlinked to them are field photographs.
WaterWells_BD	Water wells selected to give an even coverage of the study area with at least one well for each of the selected areas. Attributes include MOE water well ID number and depth (m) to bedrock
Samples_BD	Aggregate quality testing data on samples collected during OGS field work.

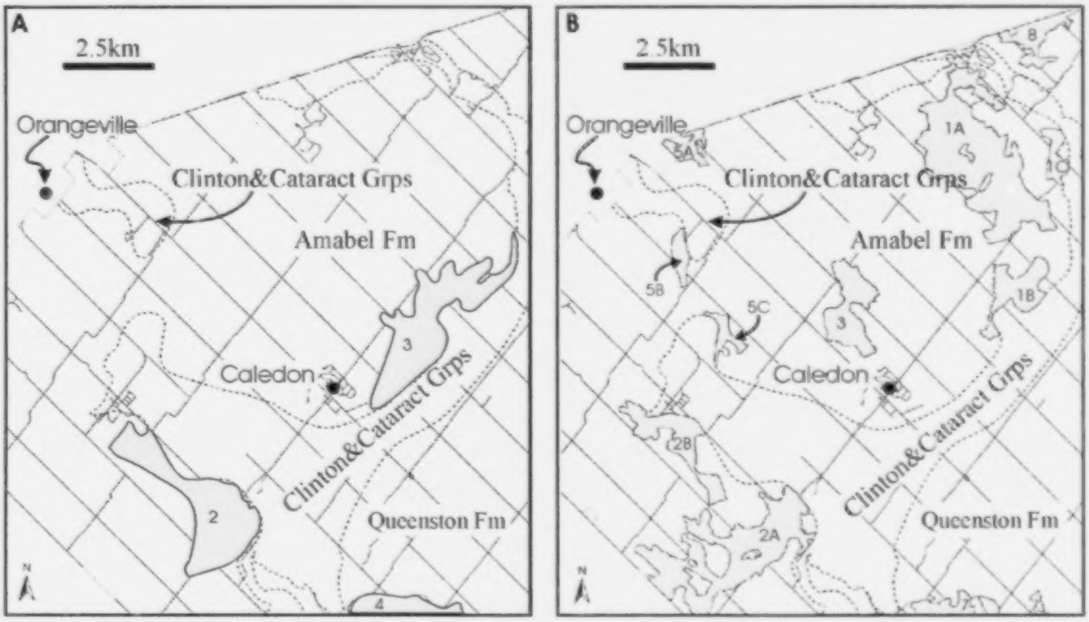

A
2.5km
Orangeville
Clinton&Cataract Grps
Amabel Fm
3
Caledon
Clinton&Cataract Grps
2
Queenston Fm
4
N
B
2.5km
Orangeville
5A
Clinton&Cataract Grps
1A
1C
B
Amabel Fm
5B
5C
3
1B
Caledon
Clinton&Cataract Grps
2B
2A
Queenston Fm
N

Figure 22.4. Bedrock resource map, northwest of the Town of Caledon, Regional Municipality of Peel, southern Ontario. Shaded/coloured polygons with number are selected resource areas. Dashed line indicates the boundaries of geological formations. A) Hand-drawn map (Golder Associates and Rowell 1996). B) Updated GIS map (Ontario Geological Survey and Golder Associates, ARIP 165–Revised, in progress). Note more resource areas have been selected than the previous map.

Select Aggregate Potential Areas

The bedrock resources are evaluated on the basis of overburden thickness in conjunction with other considerations such as aggregate suitability, size, location, and natural and cultural constraints. Areas covered by less than 8 m drift may be selected. The overburden map, which is classified into 0 to 1 m, 1 to 8 m, 8 to 15 m and over 15 m in thickness, may appear 'noisy', containing tiny polygons or 'bulls eyes' nested in polygons and 'tails' or 'horns' extending out from polygonal areas. The selected areas follow <8 m polygons, but with boundaries smoothened. Selected areas should contain sufficient data points to allow a reasonable geological interpretation. In line with the requirements for an ARIP, several map layers have been created for a GIS bedrock resources map (Table 22.3).

Using this protocol, the bedrock resources have been re-evaluated for the Regional Municipality of Peel, southern Ontario. As illustrated by Figure 22.4, the resultant map has enabled selection of several additional areas for resource protection in comparison with the old hand-drawn map that contains fewer selected areas in the northwest of the Town of Caledon.

SUMMARY

While GIS technology can not supplant field work-based geological mapping, the new approaches do provide the ability for integration and analysis of a variety of geo-data sets. This, in turn, allows enhancing map quality and confidence in geological interpretations and efficiencies in data retrieval and manipulation. In the future, Ontario Geological Survey will continue to provide GIS maps as products of its aggregate mapping program to meet demands across the province. The intense use of multiple geo-data sets means that quality control is critical and challenging in order to maintain a consistent high standard for ARIPs. Data sets, such as water wells, must be properly filtered and adequate quality control measures employed so that problematic data can be tracked, located and eliminated.

ACKNOWLEDGMENTS

R.I. Kelly, J. Dodge, R. Corcoran and S. Evers are thanked for their assistance and comments throughout the projects. Additional assistance with review was provided by C.L. Baker, the Senior Manager of the Sedimentary Geoscience Section, the Ontario Geological Survey.

REFERENCES

Baker, C.L. 2003. Aggregate resource inventory program; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.18-1 to 18-3.

Cowan, W.R. 1978. Toward the inventory of Ontario's mineral aggregates; The Canadian Mining and Metallurgical Bulletin, v.71, no.789, p.105-113.

Gao, C. 2005. GIS-based ARIP maps; Unpublished internal report, Ontario Geological Survey, 11p.

Gao, C., Shirota, J., van Haaften, S. and Brunton, F. 2005. Overburden thickness mapping and bedrock resources evaluation for ARIPs; unpublished internal report, Ontario Geological Survey, 55p.

Golder Associates and Rowell, D.J. 1996. Aggregate resources inventory of the Regional Municipality of Peel, southern Ontario; Ontario Geological Survey, Aggregate Resources Inventory Paper 165, 81p.

Kelly, R.I. and Rowell, D.J., 1995. Upgrade of aggregate resources inventory papers for the Regional Municipalities of Durham, Halton, Peel and Waterloo and the Counties of Dufferin and Wellington, southern Ontario; *in* Summary of Field Work and Other Activities 1995, Ontario Geological Survey, Miscellaneous Paper 164, p.171-172.

Mapping Service Branch 2003. Landsat-7 orthorectified imagery over Canada; Earth Science Sector, Natural Resources Canada.

Ontario Geological Survey 2003. Surficial geology of southern Ontario. Ontario Geological Survey; Miscellaneous Release—Data 128.

——— 2004. Aggregate Resources Inventory of Huron County; Ontario Geological Survey, Aggregate Resources Inventory Paper 177, 98p.

Ontario Mineral Aggregate Working Party 1977. A policy for mineral aggregate resource management in Ontario; Ministry of Natural Resources, 232p.

Rowell, D.J. and Gao, C. 2000. Aggregate resources inventory program summary; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p.32-1 to 32-3.

van Haaften, S., Shirota, J. Gao, C. and Brunton, F. 2004. Depth to bedrock: 3-dimensional bedrock and overburden thickness methodology for mineral aggregates and groundwater geology mapping in Ontario; *in* Abstracts, Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, St. Catharines, v.29, p.157.

23. Project Unit 05-021. Red Lake Area High-Density Lake Sediment and Water Survey, Northwestern Ontario

R.D. Dyer[1] **and S.M. Hamilton**[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Field work for a high-density lake sediment and water geochemical survey of the Red Lake greenstone belt was carried out between July 11 and August 4, 2005. The survey area is located approximately 400 km northwest of Thunder Bay and approximately 200 km north of Kenora (Figure 23.1). The survey completely covered the area defined by National Topographic System (NTS) 1:50 000 scale map sheets 52 K/13, 52 L/16, 52 N/4 and partially covered the area outlined by map sheet 52 M/1.

Lake sediment and water samples were collected at 1181 sites for an average of 1 sample per 3.3 km^2. This survey is the first systematic regional lake sediment geochemistry coverage to be completed over the Red Lake greenstone belt.

REGIONAL SETTING

The Red Lake district has produced over 25 million ounces of gold over the past 75 years making it a world-class mining camp. Most of this gold (over 16 million ounces) has been produced from the Campbell–Red Lake deposit (Lichtblau et al. 2005) located within the Red Lake greenstone belt.

The Red Lake greenstone belt consists of Archean supracrustal rocks of the Uchi Lake Subprovince. The most recent bedrock mapping and data compilation and interpretation of the region has been carried out under the auspices of the Western Superior NATMAP project and documented in numerous publications such as Parker (2000, 2001), Sanborn-Barrie, Skulski and Parker (2001) and Sanborn-Barrie et al. (2000, 2004). A key observation noted by Dubé, Williamson and Malo (2003) is the spatial association of most Red Lake camp gold deposits with a regional unconformity between Mesoarchean and Neoarchean rocks. In fact, the latter authors note that 94% of gold found in the district has come from deposits adjacent to this unconformity and, therefore, represents a first-order empirical exploration target. Another recent observation pertinent to gold exploration in the region is the association of significant gold mineralization with late felsic intrusions of moderate to high magnetic susceptibilities (Parker 2001).

Quaternary geological mapping of the eastern half of the study area was completed at a scale of 1:50 000 by the Ontario Geological Survey (OGS) (Prest 1981, 1982). A program of regional till sampling for indicator minerals and geochemistry was carried out by the Geological Survey of Canada (GSC) in the 1990s (Sharpe and Russell 1999); observations and airphoto interpretation during this project were combined with the existing OGS geology data and polygons to produce a 1:100 000 scale

---

Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, p 23-1 to 23-4.

© Queen's Printer for Ontario, 2005

compilation of the Red Lake–Birch–Uchi region (Sharpe and Russell 1996; Russell, Sharpe and Stacey 1999). Systematic detailed surficial geology mapping of the western half of the survey area has not been undertaken. Available data consists of reconnaissance mapping by Zoltai (1965) at a scale of 1:506 880 and a northern Ontario engineering geology terrain study (NOEGTS) at a scale of 1:100 000 (Nielson 1981), both covering only the southwestern portion of the survey area (NTS map sheet 52 L/16).

In general, the extent and thickness of drift cover decreases across the survey area from the northeast to the southwest with increasing distance away from the Lac Seul moraine. This fairly extensive drift cover over much of the eastern half of the study area, which includes significant glaciolacustrine clay deposits, has resulted in a relatively poor lake density compared to the western portion of the survey area, a region that is bedrock dominated. The presence of thick drift (including clay) is also problematic in terms of inhibiting and possibly masking the geochemical response of the underlying bedrock. The landscape variation across the study area may have a significant impact on the geochemical patterns obtained, thereby complicating geochemical data interpretation.

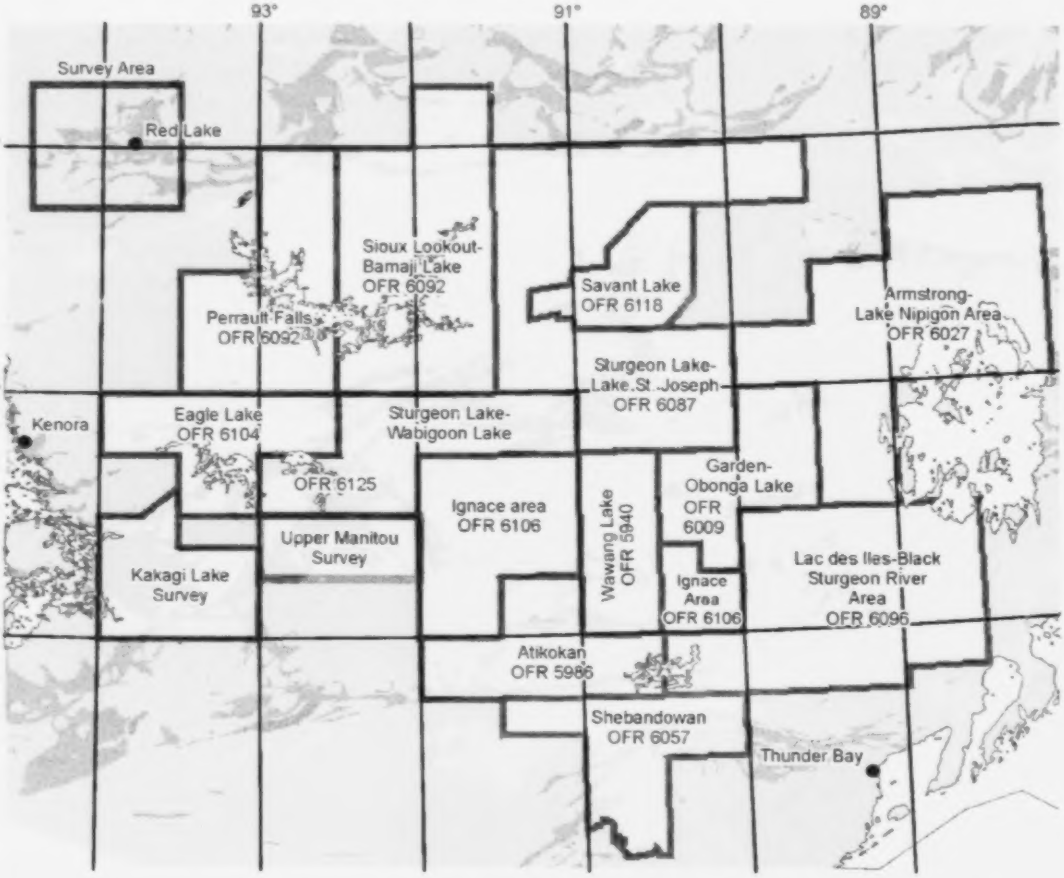

93°
91°
89°
Survey Area
Red Lake
51°
50°
49°
Kenora
Sioux Lookout-Bamaji Lake OFR 6092
Perrault Falls OFR 6092
Savant Lake OFR 6118
Armstrong-Lake Nipigon Area OFR 6027
Sturgeon Lake-Lake St. Joseph OFR 6087
Eagle Lake OFR 6104
Sturgeon Lake-Wabigoon Lake
OFR 6125
Garden-Obonga Lake OFR 6009
Ignace area OFR 6106
Wawang Lake OFR 5940
Upper Manitou Survey
Kakagi Lake Survey
Ignace Area OFR 6106
Lac des Iles-Black Sturgeon River Area OFR 6096
Atikokan OFR 5986
Shebandowan OFR 6057
Thunder Bay

Figure 23.1. Location of the Red Lake survey area and previous OGS lake sediment geochemical surveys in northwestern Ontario.

SAMPLING METHODS

Organic lake sediment samples were collected from a helicopter float using the OGS-designed gravity corer. In order to avoid anthropogenic influences and water–sediment interface effects (i.e., increased manganese due to anoxic conditions that result in secondary accumulation of base metals), only deep sediment (>20 cm below the sediment surface) was collected. This sediment better reflects the effects of natural geochemical inputs that may be traced to local geology.

Lake water samples were collected from a depth of 1.0 m using a weighted intake hose and pump. Water quality parameters such as pH, conductivity, oxidation–reduction potential and dissolved oxygen were measured at each lake site using a flow cell attached to a YSI multi-parameter probe. Lake water was pumped from each lake and allowed to purge the sampling system prior to the collection of a water sample and the recording of water quality parameters. Water samples were kept cool after collection and processed (filtered and acidified) within 6 hours of collection.

A global positioning system (GPS) receiver was utilized to record accurate sample site positions.

SAMPLE PREPARATION AND ANALYTICAL METHODS

Lake sediment samples were placed in breathable fabric bags and allowed to partially air dry prior to shipment to the laboratory. The samples were then air dried, partially pulverized in a ceramic ring and puck pulverizer and sieved to obtain the –80 mesh (<177 µm) size fraction. Laboratory analysis will include nitric-aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP–MS) to determine approximately 50 trace elements. Nitric acid-aqua regia digestion attacks all sample matrix constituents, except for silicate minerals, and, therefore, is considered a nonselective, relatively strong partial extractant.

Approximately 10 g of sample pulp are pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA) for Au, As and a suite of approximately 30 other elements. Quality control will be monitored through the use of sample pulp duplicates and certified reference materials. Loss-on-ignition (LOI) is determined at 500°C, using an automated gravimetric technique.

Water samples were passed through 0.45 µm syringe filters and acidified to 1% ultrapure nitric acid within 6 hours of collection. Analysis of water will include direct aspiration ICP–MS to determine approximately 50 elements. Quality of the analyses is monitored through the use of sample duplicates, CANMET certified reference standard SLRS-4 and distilled water blanks.

REFERENCES

Dubé, B.,Williamson, K. and Malo, M. 2003. Gold mineralization within the Red Lake mine trend: example from the Cochenour–Willans mine area, Red Lake, Ontario, with new key information from the Red Lake Mine and potential analogy with the Timmins camp; Geological Survey of Canada, Current Research 2003-C21, 15p. [electronic access only]

Lichtblau, A., Hinz, P., Ravnaas, C., Storey, C.C., Kosloski, L., Raoul, A. and Gula, R. 2005. Report of Activities 2004, Resident Geologist Program, Red Lake Regional Resident Geologist Report: Red Lake and Kenora Districts; Ontario Geological Survey, Open File Report 6146, 97p.

Nielson, J.M. 1981. Sydney Lake area (NTS 52L/NE), districts of Kenora and Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 2, 33p. Accompanied by Map 5105, scale 1:100 000.

Parker, J.R. 2000. Gold mineralization and wall rock alteration in the Red Lake greenstone belt: a regional perspective; *in* Summary of Field Work and Other Activities; Ontario Geological Survey, Open File Report 6032, p.22-1 to 22-28.

——— 2001. Intermediate to felsic plutons in the Red Lake greenstone belt: relationship to deformation and gold mineralization; *in* Summary of Field Work and Other Activities; Ontario Geological Survey, Open File Report 6070, p.19-1 to 19-10.

Prest, V.K. 1981. Quaternary geology of the Red Lake area, Kenora District (Patricia Portion); Ontario Geological Survey, Preliminary Map P.2398, scale 1:50 000.

——— 1982. Quaternary geology of the Madsen area, Kenora District (Patricia Portion). Ontario Geological Survey, Preliminary Map P.2484, scale 1:50 000.

Russell, H.A.J., Sharpe, D.R. and Stacey, P. 1999. Surficial geology of the Red Lake–Confederation Lake area, Ontario; Geological Survey of Canada, Open File D3744, digital data.

Sanborn-Barrie, M., Rogers, N., Skulski, T., Parker, J., McNicoll, V. and Devaney, J. 2004. Geology and tectonostratigraphic assemblages, east Uchi Subprovince, Red Lake and Birch–Uchi belts, Ontario; Geological Survey of Canada, Open File 4256; Ontario Geological Survey, Preliminary Map P.3460, scale 1:250 000.

Sanborn-Barrie, M., Skulski, T. and Parker, J. 2001. Three hundred million years of tectonic history recorded by the Red Lake greenstone belt, Ontario; Geological Survey of Canada, Current Research 2001-C19, 30p. [electronic access only]

Sanborn-Barrie, M., Skulski, T., Parker, J. and Dubé, B. 2000. Integrated regional analysis of the Red Lake belt and its mineral deposits, western Superior Province, Ontario; Geological Survey of Canada, Current Research 2000-C18, 16p. [electronic access only]

Sharpe, D.R. and Russell, H.A.J. 1996. Quaternary geology of the Red Lake–Confederation Lake area; Geological Survey of Canada, Open File 2876, scale 1:100 000.

——— 1999. Indicator mineral and till geochemical reconnaissance of the Red Lake/Confederation Lake area, District of Red Lake, northwestern Ontario; raw data with preliminary interpretation; Geological Survey of Canada, Open File 3038, 178p.

Zoltai, S.C. 1965. Surficial geology, Kenora–Rainy River; Ontario Department of Lands and Forests, Map S1-65, scale 1:506 880.

24. Project Unit 05-018. Gold Dispersion and Geochemical Response in Surficial Media: Implications for Data Interpretation and Exploration

R.D. Dyer[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

A project focusing on the dispersion of gold from point-source bedrock mineral occurrences and from associated glacial dispersion plumes was initiated in the Peterlong Lake to Matachewan area of northeastern Ontario during the 2005 field season (Figure 24.1). Many surficial geochemical surveys in support of mineral exploration target modern drainage media such as stream and lake sediment. This is because drainage systems are repositories of geochemical information and are considered to reflect the character and composition of the geology within the drainage catchment. Although a logical and sound concept, in practice, geochemical results can be difficult to interpret, in particular for gold, due to its unique characteristics, which often result in a heterogeneous distribution in the surficial environment.

Numerous studies have demonstrated that gold migrates from mineralized bedrock and associated till deposits into drainage pathways, including groundwater and ultimately into lake basins (e.g., Coker, Fox and Sopuck 1982; Fox, Eagles and Brooker 1986; Schmitt et al. 1993; Barnett and Dyer 2005). Opinions vary as to the mechanism of gold transport that operates on the low-relief Canadian Shield. For example, Fox, Eagles and Brooker (1986) comment that, "…it is unlikely that dense particulate gold would be transported for any significant distance from source". Conversely, S. Averill (Overburden Drilling Management, written communication, 2003) is a strong proponent of the opposite view, that most gold anomalies in lake sediment, soil and even humus samples are caused by physical gold particles, not by chemically adsorbed gold. However, an excellent study by Schmitt et al. (1993) reached the conclusion that, "Au may be transported in both clastic and soluble form, with the local environment determining the relative importance".

Therefore, regardless of the mode of transport, landscape complexity clearly plays a role in the geochemical patterns observed (or lack of); however, other factors that may have a significant impact on gold include sampling methods, sample size, sample preparation procedures, precision and accuracy of laboratory analysis, and the classic nugget effect. In support of this project, samples of till, stream sediment and lake sediment were sampled near (and, where appropriate, in the down-ice and up-ice direction) existing bedrock gold occurrences, lake sediment anomalies and till anomalies (containing anomalous levels of gold grains). Sampling in support of building dispersion case histories was undertaken in the townships of Beemer, Bartlett, English, Semple, Zavitz and Flavelle (Figure 24.2).

BACKGROUND

In large part, the impetus for this project has been the reliability of regional geochemical surveys (in particular lake sediment surveys) to adequately assess gold potential. Recent work by the Ontario

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.24-1 to 24-8.

© Queen's Printer for Ontario, 2005

Geological Survey (OGS) (specifically several projects under the Operation Treasure Hunt program) have encountered difficulties with the apparent severe inhomogeneity of gold concentrations in surficial media samples. Highly disparate results from the same sample pulp sent for instrumental neutron activation analysis (INAA) and fire assay–inductively coupled plasma mass spectrometry (FA-ICP–MS) for Au analysis have been common (Table 24.1). Similar problems with reproducing Au results by re-sampling have been encountered by the OGS (Table 24.2) and others (e.g., Thomas 1986). Preliminary work (examination of quality control standards) has ruled out laboratory error; therefore, this problem is more likely a sampling issue, exacerbated by the classic "nugget effect". For example, sample size is important with any media in order to obtain a representative sample and to help overcome heterogeneity. Lake sediment samples collected by the OGS have a maximum volume of ~1 L and a wet weight of ~1 kg. However, after drying, a loss of 85% weight is typical, resulting in an average sample size of 50 g. Although organic lake sediments are considered very homogeneous, such a small sample size may not be adequate to overcome the inherent heterogeneous nature of gold distribution. The assumption that homogeneous organic lake sediments are relatively unaffected by this phenomenon (largely due to the presumed dominance of hydromorphically transported gold) has come into question. The level of confidence in reporting Au anomalies in reports and data releases to the public has suffered as a result.

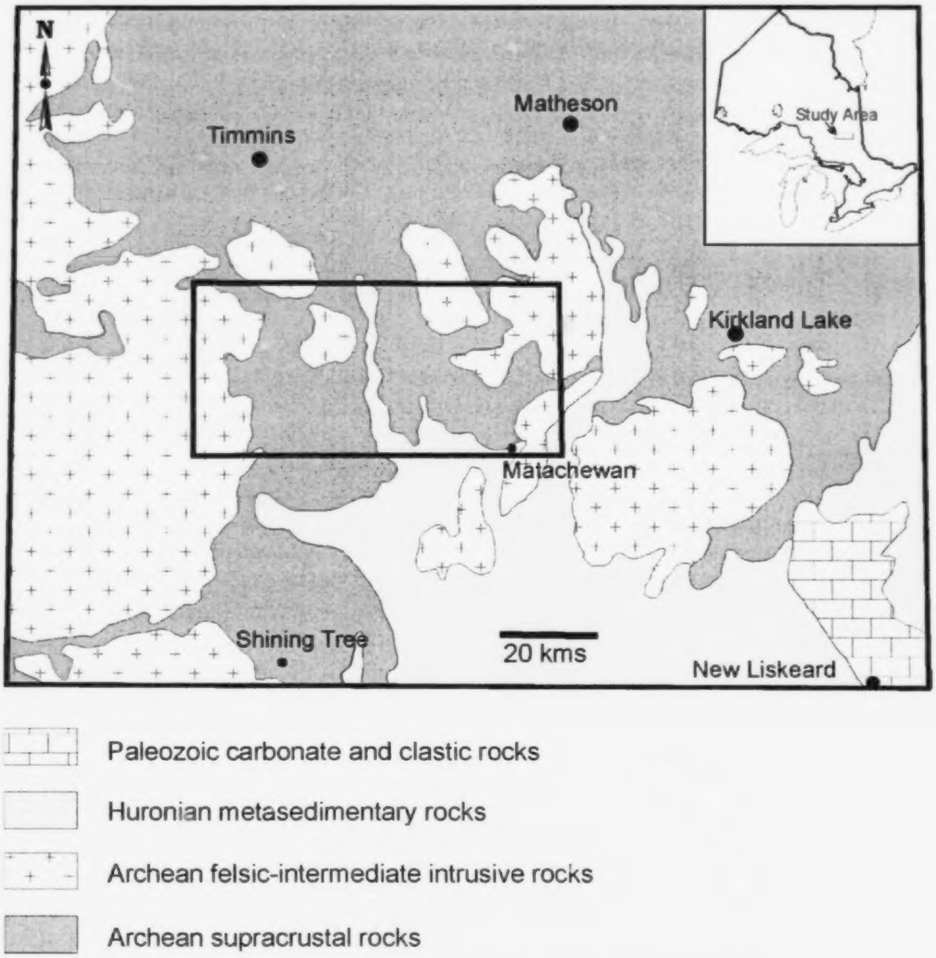

N
Matheson
Timmins
Study Area
Kirkland Lake
Matachewan
Shining Tree
20 kms
New Liskeard
Paleozoic carbonate and clastic rocks
Huronian metasedimentary rocks
Archean felsic-intermediate intrusive rocks
Archean supracrustal rocks

Figure 24.1. Location of study area, southern Abitibi greenstone belt.

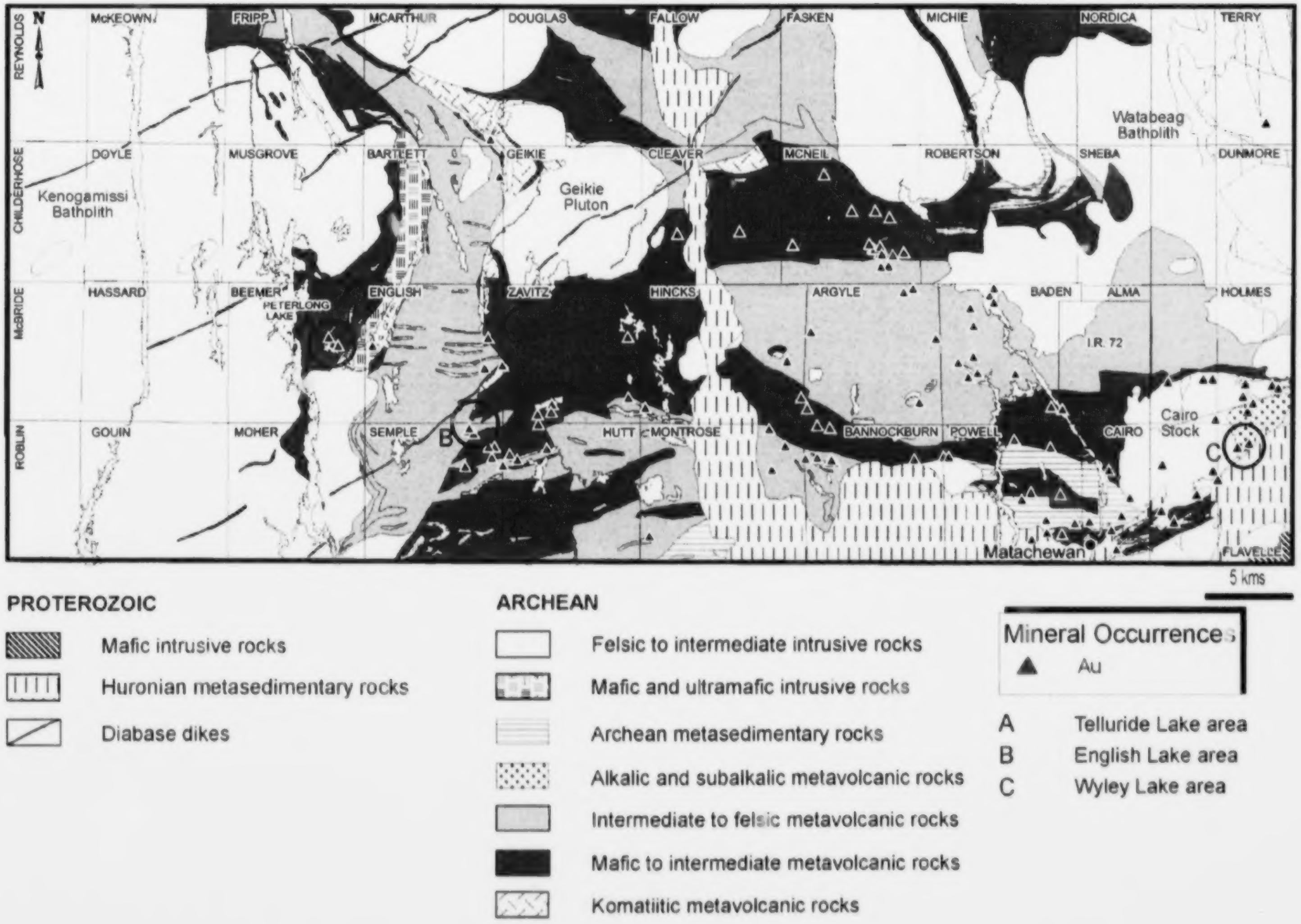

N
REYNOLDS
McKEOWN
FRIPP
MCARTHUR
DOUGLAS
FALLOW
FASKEN
MICHIE
NORDICA
TERRY
CHILDERHOSE
DOYLE
MUSGROVE
BARTLETT
GEIKIE
CLEAVER
MCNEIL
ROBERTSON
SHEBA
DUNMORE
Kenogamissi Batholith
Geikie Pluton
Watabeag Batholith
McBRIDE
HASSARD
BEEMER
PETERLONG LAKE
ENGLISH
ZAVITZ
HINCKS
ARGYLE
BADEN
ALMA
HOLMES
I.R. 72
ROBLIN
GOUIN
MOHER
SEMPLE
HUTT
MONTROSE
BANNOCKBURN
POWELL
CAIRO
Cairo Stock
Matachewan
FLAVELLE
B
C
5 kms
PROTEROZOIC
Mafic intrusive rocks
Huronian metasedimentary rocks
Diabase dikes
ARCHEAN
Felsic to intermediate intrusive rocks
Mafic and ultramafic intrusive rocks
Archean metasedimentary rocks
Alkalic and subalkalic metavolcanic rocks
Intermediate to felsic metavolcanic rocks
Mafic to intermediate metavolcanic rocks
Komatiitic metavolcanic rocks
Mineral Occurrences
▲ Au
A Telluride Lake area
B English Lake area
C Wyley Lake area

Figure 24.2. Location of detailed study areas within the Peterlong–Matachewan portion of the southern Abitibi greenstone belt (geology *from* Ayer et al. 2003).

Table 24.1. Comparison of gold results by fire assay (FA), INAA and micro-panning.

Lake Sediments (–80 mesh pulp)	Au by FA (ppb)	Au by INAA (ppb)	Calculated ppb Au (ODM)*
01-LS-0017	12.4	<2	n/a
01-LS-0064	30.0	<2	n/a
01-LS-0289	35.2	<2	n/a
01-LS-0507	1.8	16	n/a
01-LS-0550	16.7	<2	n/a
01-LS-0611	2.6	41	n/a
01-LS-0639	2.5	20	n/a
01-LS-0722	1.9	31	n/a
01-LS-0993	13.5	<2	n/a
01-LS-1083	2.6	40	n/a
01-LS-1098	57.3	<2	n/a
01-LS-1200	1.0	61	0
01-LS-1244	1.8	59	0
01-LS-1255	22.4	<2	n/a
01-LS-1485	11.9	<2	n/a
01-LS-1639	1.0	74	0
01-LS-1815	2.0	29	n/a
01-LS-2056	66.4	<2	n/a
01-LS-2135	2.8	21	n/a
01-LS-2161	2.6	22	n/a
01-LS-2342	<1	15	n/a
01-LS-2470	2.0	17	n/a
01-LS-2578	1.0	23	n/a
01-LS-2582	<1	15	n/a
01-LS-2585	1.6	24	n/a
01-LS-2592	23.6	3	n/a
01-LS-3739	78.0	<2	0
01-LS-4158	101.9	<2	0

Stream sediments (–80 mesh pulp)	Au by FA (ppb)	Au by INAA (ppb)	Calculated ppb Au (ODM)**
01-SS-139	<1	365	321
01-SS-226	27.3	84	54
01-SS-229	1.2	338	317
01-SS-329	<1	130	255
01-SS-346	144.5	35	0
01-SS-419	<1	160	260
01-SS-585	<1	622	712
01-SS-586	25.8	64	0
01-SS-624	2.0	623	1082
01-SS-666	96.3	55	13
01-SS-772	n/a	266	208

* based on micro-panning of remaining –80 mesh fine pulp

** based on micro-panning of irradiated INAA material

Table 24.2. Comparison of gold results by fire assay (FA) and INAA from field duplicates.

Lake Sediments (–80 mesh pulp)	Original Sample Au by FA (ppb)	Field Duplicate Au by FA (ppb)	Original Sample Au by INAA (ppb)	Field Duplicate Au by INAA (ppb)
01-LSS-658	<2	<2	<2	7
01-LSS-778	<2	<2	10	4
01-LSS-831	<2	<2	<2	8
01-LSS-963	<2	<2	8	<2
01-LSS-1297	41.1	2.1	<2	<2
01-LSS-1316	2.3	<2	9	16
01-LSS-1350	<2	n/a	20	<2
01-LSS-1370	<2	21.8	5	6
01-LSS-2087	<2	<2	<2	20
01-LSS-2182	15.3	<2	<2	<2
01-LSS-2294	<2	13.9	<2	<2
01-LSS-2567	10.7	6.2	5	<2
01-LSS-2692	<2	9.5	<2	<2
01-LSS-2843	<2	n/a	8	<2
01-LSS-2878	3.3	13.8	<2	<2
01-LSS-3974	28.0	2.2	<2	<2
01-LSS-4462	10.1	<2	<2	<2
01-LSS-4610	<2	6.7	<2	<2

Note: field duplicates were collected approximately 1 month after original samples were obtained.

Results of recent surficial geochemical studies by the OGS (e.g., Barnett and Dyer 2005) have re-emphasized the importance of landscape conditions on the interpretation of lake sediment geochemistry. Specifically, lakes located on "simple" bedrock-dominated terrain, compared to lakes on more "complex" organic and/or glacial deposit-dominated terrain, not only can differ in the assemblage of elements accumulated in the sediment, but also in their absolute values (geochemical intensity). This difference in intensity can be problematic for precious metals, such as Au, Pd and Pt, which are considered geochemically significant (anomalous) at relatively low concentrations.

PROJECT OBJECTIVES

This project will address a number of issues, including:

- How does landscape variability rank (compared to other factors such as type of underlying bedrock geology, level of organic and inorganic content of the sampled sediment) as a factor affecting the geochemistry of Au in lake sediments?
- Can this variability be reliably filtered out or compensated for during data processing?
- Under what environment(s) does clastic or physical transport of Au predominate over hydromorphic transport, or vice versa?
- Are the current methods of sampling and analysis of lake sediments adequate for the determination of precious metals such as gold?

- Would a weaker digestion or leach method be more suitable for gold determinations? (e.g., Mobile Metal Ion (MMI) Process™, Enzyme Leach^{SM})
- What is the most reliable method for Au determinations in surficial media. Does it depend to any degree on the type of surficial media?
- What is the optimum sample handling procedure, through initial collection in the field to final analysis at the laboratory?
- Does or can gold or any other heavy minerals "settle out" within a prepared fine pulp during transport to the laboratory, resulting in heterogeneous gold distribution?
- What is the best analytical method for the determination of Au in lake sediment? What size fraction of lake sediment is optimum?
- For INAA analysis of Au in lake sediment, is epithermal or thermal irradiation best? How do the results for Au analysis compare between these methods?

The answers to these questions have a direct bearing on the quality and reliability of data releases and interpretation, whose objectives are to assist explorationists by publishing the highest quality, reliable, "added value" reports and data sets.

FIELD WORK

Suitable gold dispersion study areas to build case histories were guided by the presence of at least 3 characteristics: the presence of an existing Au showing in bedrock; an associated gold anomaly in surficial media (till or lake sediment); and a nearby lake within the drainage watershed of the bedrock gold occurrence. A portion of the Abitibi greenstone belt, south of Timmins between Matachewan and Peterlong Lake, was chosen for this project due to the abundance of gold showings (*see* Figure 24.2) and the wealth of recent data for the area including Quaternary mapping (Bajc and Paterson 2000a, 2000b), till geochemistry and indicator mineral sampling (Bajc 1996; Bajc et al. 1996; Bajc 1997; Bajc and Crabtree 2001), bedrock mapping (Ayer et al. 2003; Berger 2004; Berger and Préfontaine, this volume; Préfontaine and Berger, this volume) and lake sediment geochemistry (Bajc et al. 1996; OGS 2001).

Three lakes with nearby gold occurrences were identified for detailed investigation (*see* Figure 24.2). Two of these (Telluride Lake and English Lake) also have significant (anomalous) gold grains in till (up to 33 grains) in their general area (Bajc 1996). The third lake (Wyley Lake) has a very strong Au anomaly (132 ppb by FA-ICP–MS and 434 ppb by INAA) in lake sediment (Bajc et al. 1996; OGS 2001). A total of 55 lake sediment samples, 27 "C"-horizon till samples, 8 stream sediment and 6 rock samples were collected. At each lake sediment sample site, 2 samples were collected using the OGS torpedo coring apparatus and one large sample with an Ekman dredge. The Ekman dredge was used in order to obtain a bulk sample for tabling and micro-panning to isolate any gold grains. Till samples (typically between 15 to 20 kg) were taken to verify (and attempt to repeat) the previous Au grain results and to better define the extent and direction of glacial dispersion trains related to the gold occurrences. A smaller ~1.5 kg sample was also taken to be analyzed by conventional fine fraction (–63 μm) geochemistry.

Additional lake sediment sampling was undertaken at 2 lakes (Muskasenda and Dill lakes), which have previously been identified as having anomalous gold levels by OGS sampling (Bajc et al. 1996; Dyer, Takats and Felix 2004). At each of these lakes, a bulk sample of approximately 40 L of material was obtained using an Ekman dredge, in addition to smaller conventional samples by the OGS torpedo.

SAMPLE PREPARATION AND ANALYSIS

Lake sediment samples (~1 to 1.5 kg) collected by torpedo coring were placed in breathable fabric bags and allowed to partially air dry prior to oven drying at 35°C. Samples collected by Ekman dredge (~4 to 10 kg) were double bagged in large plastic bags. Till and stream sediment samples were also collected in large plastic bags after being passed through a 5 mm screen. Approximately 30 to 50 pebbles were collected from each sample for pebble lithology study.

The bulk samples of till and lake sediment will be submitted to Overburden Drilling Management (ODM) for tabling to isolate a heavy mineral concentrate followed by micro-panning to accurately determine gold content. Gold grain morphology will be classified as described by Averill (2001) and a gold concentration in ppb will be calculated based on the size dimensions of the grains recovered.

The conventional lake sediment samples obtained by gravity coring (~1 to 1.5 kg), after drying, will be gently disaggregated followed by sieving at 80 mesh to isolate the –177 µm size fraction. Based on previous experience, the resulting prepared sample pulp will range between 50 and 150 g. The entire prepared pulp will be separated into aliquots and consumed for replicate analysis by INAA (thermal and epithermal irradiation), FA-ICP–MS, Mobile Metal Ion Process™ (MMI) and Enzyme Leach^{SM}. After a suitable period of cooling, the INAA briquettes will be submitted to ODM for micro-panning to isolate any gold grains and determine grain morphology.

The bulk 40 L samples of lake sediment will be homogenized and then split in half with one portion going to ODM for gold grain counting. The remaining half will be dried and sieved and multiple aliquots analyzed for Au by INAA, FA-ICP–MS, MMI and Enzyme Leach^{SM}.

In addition to the gold analysis, 0.5 g of material from each sample will be digested in nitric-aqua regia followed by inductively coupled plasma mass spectrometry (ICP–MS) to determine approximately 50 trace elements. The INAA analysis will also provide arsenic data and a suite of approximately 30 other elements. Quality control will be monitored through the use of replicate analysis of OGS reference materials and certified reference materials. Loss-on-ignition (LOI) is determined at 500°C, using an automated gravimetric technique.

DISCUSSION

The initial goals of the sampling and analytical strategy of this project, which will potentially have an immediate impact on OGS lake sediment methodologies, are fourfold:

1. Determine the optimum initial (field) sample size for lake sediments and optimum sub-sample size for analysis;
2. Determine the optimum and most cost-effective analytical method for gold;
3. Determine the history of gold transport into the lake basin (physical and/or hydromorphic transport);
4. Determine the effect of local landscape conditions on gold transport into the lake basins.

This project will benefit both the OGS and clients by enhancing understanding of the dispersion and character of gold within various surficial media from differing landscapes; determining optimum methods (both sampling and analytical), particularly for lake sediments; and assisting geochemical data interpretation. The large geochemical data sets obtained over the past 4 years have been published relatively quickly, with minimal interpretation, largely due to time constraints, but also because of gaps in our own knowledge of how the varied and complex landscapes in Ontario respond geochemically. This project will help address this issue as well as serve as a foundation for future interpretation of the analytical results from surficial media geochemical projects such as regional high density lake sediment surveys.

REFERENCES

Averill, S.A. 2001. The application of heavy mineral indicator mineralogy in mineral exploration with emphasis on base metal indicators in glaciated metamorphic and plutonic terrains; *in* Drift exploration in glaciated terrain, Geological Society, London, Special Publication No.185, p.69-81.

Ayer, J.A., Trowell, N.F., Josey, S., Nevills, M. and Valade, L. 2003. Geological compilation of the Matachewan area, Abitibi greenstone belt; Ontario Geological Survey, Preliminary Map P.3527, scale 1:1000 000.

Bajc, A.F. 1996. Regional distribution of gold in till in the Peterlong Lake–Radisson Lake area, southern Abitibi Subprovince; potential exploration targets; Ontario Geological Survey, Open File Report 5941, 57p.

——— 1997. A regional evaluation of gold potential along the western extension of the Larder Lake–Cadillac break, Matachewan area: results of regional till sampling; Ontario Geological Survey, Open File Report 5957, 50p.

Bajc, A.F. and Crabtree, D.C. 2001. Results of regional till sampling for kimberlite and base metal indicator minerals, Peterlong Lake–Radisson Lake area, northeastern Ontario; Ontario Geological Survey, Open File Report 6060, 65p.

Bajc, A.F., Hamilton, S.M., Ayer, J. and Jenson, L.S. 1996. New exploration targets in the Peterlong Lake–Radisson Lake area, southern Abitibi subprovince; till, lake sediment and lake water sampling programs; Ontario Geological Survey, Open File Report 5942, 129p.

Bajc, A.F. and Paterson, J.T. 2000a. Quaternary geology of the Radisson Lake area, northeastern Ontario; Ontario Geological Survey, Map 2610, scale 1:50 000.

——— 2000b. Quaternary geology of the Peterlong Lake area, northeastern Ontario; Ontario Geological Survey, Map 2611, scale 1:50 000.

Barnett, P.J. and Dyer, R.D. 2005. Surficial geochemistry case studies project, Lake Nipigon region geoscience initiative; Ontario Geological Survey; Open File Report 6167, 144p.

Berger, B.R. 2004. Geology of Burt–Holmes area, District of Timiskaming; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.5-1 to 5-9.

Coker, W.B., Fox, J.S. and Sopuck, V.J. 1982. Organic centre–lake sediments: application in the geochemical exploration for gold in the Canadian Shield of Saskatchewan; *in* Geology of Canadian gold deposits, Canadian Institute of Mining and Metallurgy, Special Volume 24, p.267-280.

Dyer, R.D., Takats, P.A. and Felix, V.E. 2004. Sudbury area lake sediment geochemical survey; Ontario Geological Survey, Open File Report 6126, 106p.

Fox, J.S., Eagles, T. and Brooker, E. 1987. Exploration Technology Development Program, Grant No. 090: The use of direct lake sediment geochemical sampling for gold as a reconnaissance precious metal exploration tool in the Canadian Shield; Ontario Geological Survey, Open File Report 5669, 57p.

Ontario Geological Survey 2001. Peterlong Lake–Radisson Lake area high density lake sediment survey: gold and PGE data – Operation Treasure Hunt; Ontario Geological Survey, Open File Report 6053, 46p.

Schmitt, H.R., Cameron, E.M., Hall, G.E.M. and Vaive, J. 1993. Mobilization of gold into lake sediments from acid and alkaline mineralized environments in the southern Canadian Shield: Gold in lake sediments and natural waters; Journal of Geochemical Exploration, v.48, p.329-358.

Thomas, M.W. 1986. Lake sediment gold anomalies: follow-up survey; *in* Summary of investigations 1986, Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 86-4, p.72-75.

25. Project Unit 02-018. Three-Dimensional Modelling of Quaternary Deposits in Waterloo Region, Ontario: A Case Study Using Datamine Studio® Software

A.F. Bajc[1] and M.J. Newton[2]

[1]Sedimentary Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[2]Datamine Corporate, 2 St. Cuthbert's Street, Wells, Somerset BA5 2AW, United Kingdom

---

INTRODUCTION

With the recent release of draft legislation on the development and approval of watershed-based source protection plans, the Government of Ontario is implementing one of the key recommendations stemming from the Walkerton Inquiry (O'Connor 2002). The input of geological information is critical for the successful development and implementation of source protection plans for all regions of the province. To this end, the Ontario Geological Survey (OGS) has embarked on a new program designed to provide basic geoscience information for the protection and preservation of the provincial groundwater resource.

A pilot project of three-dimensional (3D) mapping of Quaternary deposits within Waterloo Region was initiated in 2002 as part of this geoscience initiative. The objectives of this project were to develop protocols for the construction of interactive 3D models of Quaternary geology and derived products that could 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. Waterloo Region was one of 2 areas chosen for this pilot project as it is one of the largest municipal users of groundwater in Canada, relying almost exclusively on bedrock and overburden aquifers for their potable water supply. Waterloo Region also has a population that is projected to increase by an estimated 20% in the next decade. This dramatic increase will undoubtedly apply pressure to an already stressed groundwater resource. A better understanding of the geometry and inherent properties of the Quaternary sediments that overlie the bedrock surface within the region will assist with the development of source water protection plans and with the development of a geoscience-based management plan for the groundwater resource.

Summaries of Quaternary geology, data compilation and standardization and new programs of data acquisition undertaken as part of this project are contained in OGS *Summary of Field Work and Other Activities* articles (Bajc 2002, 2004; Bajc et al. 2003) as well as in a guidebook for a Geological Association of Canada field trip (Bajc and Karrow 2004). This article briefly describes the protocols developed for the construction of a three-dimensional model of the Quaternary sediments overlying bedrock in Waterloo Region.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.25-1 to 25-8.

© Queen's Printer for Ontario, 2005

THE DATABASE AND CONCEPTUAL GEOLOGICAL MODEL

The subsurface database for Waterloo Region, an area of just under 1400 km^2, contains approximately 26 000 records and nearly 73 000 sediment layers. Nearly 20% of the borings are classed as "definitive", which means that they were logged by a trained geoscientist. These definitive boreholes consist of monitoring wells, engineering test holes, natural and man-made exposures and cored borings. The data set currently contains approximately 110 cored boreholes within the region, 13 of which were completed as part of this project. These "golden spikes" are an invaluable source of stratigraphic information and are essential for the development and verification of the conceptual geological model. In addition, approximately 450 geophysically interpreted borehole logs, 17.5 km of seismic reflection data and 16 km of ground-penetrating radar data served to assist with the interpretation.

The conceptual geological model developed for the Region of Waterloo consists of an aquifer–aquitard sequence with 19 layers. Many of these layers have limited aerial extent, their outer edges defined by the limits of ice advance, the elevation of meltwater channels and other paleotopographic controls. The model development approach involved subdivision of the Quaternary sequence, to as high a level as possible, bearing in mind that units could be merged if data quality prevented their full definition from a regional perspective. The time-transgressive nature of some of these units proved difficult to model in 3 dimensions. For example, an ice advance and retreat sequence will result in the deposition of a layer of till out to a given ice margin. Beyond the ice margin, there is continuous deposition of glaciofluvial and/or glaciolacustrine sediment, whereas, inside the ice margin, the stratified deposits are subdivided into an upper and lower sequence separated by a layer of till. It is difficult to subdivide the stratified deposits beyond the ice margin into a similar upper and lower sequence as data quality generally prevents this. Similar bifurcating sequences occur in till units along the eastern and western edges of the region. In the east, a single layer of Port Stanley Till may correlate and span the same time interval as 3 layers of till in the central parts of the region (e.g., Catfish Creek, Maryhill and Port Stanley tills). Diachronic subdivision of Port Stanley Till along the eastern margin of the region was not attempted. Rather, a lithostratigraphic approach was chosen, whereby, Port Stanley Till was lumped as a single unit.

INTERPRETATION

Two tables were created during the assembly of the subsurface database. These include a "Location" table, which contains information about the borehole such as its original identification, source, location (X,Y,Z) and boring type, and a "Formation" table, which contains descriptive information regarding the sediment layers present in each borehole. Included in the "Formation" table was a "Formation" field where a stratigraphic interpretation of the layer described could be included (e.g., Port Stanley Till, Catfish Creek Till, Canning Till …). This interpretation was generally available for cored boreholes and from logs of surface exposures described as part of Quaternary mapping programs and other field investigations. The tops of units with "Formation" identifiers were later translated to the aquifer/aquitard scheme and exported to a "Picks" table containing "X,Y,Z" and "STRATUM" attributes. "Bedrock" and "DeepOB" picks were also included in this table. "DeepOB" picks were determined by interpolating a "Bedrock" surface in ESRI® ArcInfo® software using "Bedrock" picks only, then searching for deep overburden boreholes that pierce the bedrock surface. The elevation of the bottom of these boreholes was then added to the "Picks" table and attributed as "DeepOB" picks. By applying this method of "push-down", it is less likely to miss potential buried bedrock valleys defined by deep overburden wells. This table of "definitive" picks was then used to generate a series of "training" surfaces to work from and guide further interpretations of lower quality borehole information. Viewlog® software was used initially in the interpretation process to pick formation tops from lower quality boreholes.

In an attempt to ensure that the three-dimensional model honoured materials mapped at the surface, the surficial units present on the 1:50 000 scale Quaternary geology maps were translated to the 19 layer stratigraphic model. Only 8 of the19 layers are represented by surface sediments in Waterloo Region. For example, areas mapped as Mornington Till were translated to hydrostratigraphic unit "ATB1" and areas mapped as glaciofluvial outwash were translated to hydrostratigraphic unit "AFA2". The provincial digital elevation model (DEM) was then sampled on a 200 m spacing producing a secondary picks table with "X,Y,Z" co-ordinates populated with the attribute "STRATUM" representing the surface material at that site. This table contains over 39 000 entries. A serious discrepancy was found between areas mapped as ice-contact stratified drift (AFB1) and the uppermost strata of boreholes in these areas. This is not unexpected as morainic areas tend to be heterogeneous. For this reason, it was decided to omit these points (AFB1) from the secondary picks table and rely exclusively on the borehole records from these areas to define where the aquifer (AFB1) is confined versus unconfined. This reduced surface picks table has nearly 32 000 entries. The surficial geology map showed a close correspondence with the borehole information in the remaining regions.

MODELLING

The approach taken for modelling the Quaternary deposits in Waterloo Region is slightly different than that followed by other jurisdictions doing regional three-dimensional modelling. For example, the Geological Survey of Canada opted for an automated approach guided by expert knowledge and a conceptual stratigraphic framework in its regional assessment of the Oak Ridges Moraine (Logan et al., in press). The Illinois State Geological Survey, in its three-dimensional study of Antioch Quadrangle, chose to evaluate and pre-screen the greater than 4000 drill logs that exist for this area and base their model on the "best" 275 borehole records (Hansel, Stiff and Barnhardt 2004). For the Waterloo study, a decision was made to manually interpret, where possible, the 26 000 borehole records in section guided by the training surfaces and attempt to selectively extract as much information as possible from logs of disparate or lower quality. Although considered to be a poor source of subsurface information, water well records frequently contain valuable information concerning the tops of bedrock and important aquifer and aquitard units. Seeing that most water wells are screened in the first productive, water-bearing horizon, one can feel fairly confident that the lowest unit in a given water well is an aquifer. The tops of these units form an important component of our picks table.

A number of software packages were looked at and evaluated for their ability to meet our specific 3D mapping needs. The main elements of interest in a software program were 1) strong 3D visualization capability for data interpretation; 2) excellent linkage and live update capacity with the working database; 3) ability to interpolate surfaces and apply logical rules that allow for laws of superposition to be honoured; 4) ability to create wireframe surfaces, solid models; 5) ability to calculate volumes of solids; 6) ability to import ArcInfo® shape files and drape base information over a 3D model; 7) ability to import raster images such as seismic sections into the model for added interpretation; 8) ability to create isopach maps of individual strata; 9) ability to create elevation maps of the tops of individual strata; 10) ability to export, in ASCII format, top of formation data at a specified grid spacing; and 11) the ability to provide a free viewing software that allows for flexible client interaction with the 3D model. Datamine Studio®, a software package used primarily by the mining sector for mine design and orebody modelling, was chosen for this study. This software met all of the criteria listed above and appeared to be suitable for 3D modelling of complex Quaternary sequences where units frequently pinch out forming lenses. This software has also been successfully used in the coal mining industry to similarly model discontinuous lenses and seams of coal.

Another strength of Datamine Studio® that was used to great effect on this project is the customizable interface that allows a series of repeatable tasks to be defined and presented to the user through a scripted interface using the same tools that are available for creating Web sites. This makes it very easy for the user to carry out complex modelling procedures.

The Datamine Solution

In a process similar to that undertaken with Viewlog® software, the drill-hole database was further examined in Datamine Studio® along east-west sections spaced at 100 m with 50 m offset, or clipping, limits. A set of scripts were created to assist with the display and manipulation of the drill-hole and picks data. This process allowed for a refinement of the picks table generated initially in Viewlog®. In most cases, the upper surface of a given stratum was identified by creating a 3D point on the drill hole. Alternatively, 3D points were digitized off drill holes to assist with the refinement of stratum geometry. Over 38 000 picks have been created to date in this manner. As mentioned previously, we also have nearly 32 000 3D surface data points sampled from the DEM on a 200 m square grid that can optionally be used in conjunction with the picks data.

If all strata could be identified in all boreholes then modelling would be a straightforward process. However, because of data quality and varying borehole depth, there are on average only 2.2 strata identified per hole suggesting a fair amount of missing information. In addition, not all strata exist over the entire area, so there are holes in and limits to the surfaces. The simplest method would be to create a digital terrain model (DTM) wireframe surface for each stratum from the known picks. However, because of the scarcity of the data for some layers, this leads to a large number of overlaps between the surfaces that are difficult to adjust. An alternative approach would be to interpolate the elevations for each stratum onto a regular grid using inverse power of distance or normal kriging and then apply a suite of rules to sort out the overlaps. In this instance, the rules would be complex as they would need to take into account both the sequence of strata at every model column and also the elevations of the strata in adjacent columns of cells in order to avoid large steps in elevation between the cells. To avoid this problem, the method selected was to interpolate the stratum elevations onto each borehole, apply a set of rules to resolve any overlaps within the holes and then to create a DTM wireframe surface for each stratum. This method ensured that the wireframes do not overlap. The spaces between each successive pair of wireframes are then filled with model cells in order to create a block model of the aquifers and aquitards.

The process for creating the models is very much an iterative one. The models are created using the initial data and then they are checked visually in the 2D and 3D graphics windows. Data problems are identified and fixed, and extra data are added to control the position of the strata. A new set of models are then generated and validated and the process repeated. In order to facilitate the procedure, the total area can be divided into user defined subareas and models generated for each.

DATA PREPARATION

The system that has been implemented allows the option of whether to use just the digitized picks or both the digitized picks plus the surface picks. Where digitized picks correspond to positions down a borehole, the borehole collar elevation is retrieved from the COLLARS file. Where digitized picks do not correspond to a borehole, the points are projected onto the topography wireframe in order to find the topography elevation. Although the description in the previous section refers to interpolation onto the borehole, in practice, a 2D block model is generated with cell centres at each X,Y location in the picks file. Therefore, some of the cells include several picks, whereas others will include just a single pick as is the case with the surface pick points. All cells will also include the topography elevation.

The data are initially validated to ensure that the elevations for all picks are in the correct sequence. If any inconsistencies are found, then the data for that cell is copied to an errors file, and is removed from the current run. The problem picks can then be edited before any subsequent runs of the system occur.

INTERPOLATING ELEVATIONS

The model cells are reformatted into a 2D point data file, which is then used to estimate elevations of every stratum into every cell. These estimates are combined with the actual picked elevations so that if an actual pick value exists, the estimate is discarded. If there are insufficient data within the search radius, then an absent data elevation is assigned. The estimation process allows for a full range of interpolation methods to be selected. This includes polygonal, inverse power of distance and various types of kriging. Currently, isotropic inverse square of distance is used. The search radius was manually assigned for each stratum. This was done by creating a DTM from the actual picks and varying the maximum length of the edge of any triangle until a suitable value was achieved (i.e., the modelled extent of the given stratum appeared to closely reflect its perceived extent). Search radii vary from 1000 to 3000 m. Larger search radii were used for strata that are considered to be more continuous such as bedrock and the Catfish Creek Till. In addition, aquitards were assigned larger search radii, since they are assumed to be more continuous than aquifers. A minimum of 3 data points are required for most strata inside the search area before the elevation is interpolated. This variable is adjustable as well.

CREATING THE DIGITAL TERRAIN MODELS

At the end of the interpolation stage, every stratum in every cell will have one of the following elevation values: 1) an actual value defined by a pick; 2) an estimated value defined by interpolation; or 3) absent data indicating insufficient data exists within the search area. However, because of the sparsity of the data and the large number of estimated values, elevations are frequently out of sequence. To correct this, the following rules were applied where Z(n) is the elevation of stratum "n" with 1 being the youngest (top elevation) and 19 being the oldest (lowest elevation). The rules are applied to each stratum in turn starting from bedrock (n=19) and working up to ATA1 (n=1). Lower and upper strata refer to the stratum immediately below or above the current stratum.

- If Z(19) = absent, then exit.
  i.e., make sure bedrock Z(19) is estimated into all cells. Otherwise exit.
- If Z(n) is an actual pick, then no adjustment will be made.
  The following adjustments, therefore, only apply to estimated or absent values.
- If $Z(n) < Z(n+1)$, then $Z(n) = Z(n+1)$
  i.e., if the elevation of the current stratum is estimated below the lower stratum, then set it equal to the elevation of the lower stratum. This means the thickness is estimated as zero.
- If Z(n) = absent, then $Z(n) = (Zn+1)$
  i.e., if the elevation of the current stratum is absent, then set it equal to the elevation of the lower stratum. This means the stratum is being pinched out on the lower stratum.
- If Z(n-1) is "actual" and $Z(n) > Z(n-1)$, then $Z(n) = Z(n-1)$
  If the upper stratum is an actual value and the elevation of the current stratum is estimated to be above the upper stratum, then reset it equal to the upper stratum. In this case, the current stratum should actually be reset to the base of the upper stratum. This is difficult to achieve in an automated fashion since the base of the upper stratum may not be defined. These picks need to be flagged for manual adjustment.

Using the above rules, it is still possible to have strata out of sequence and so a second set of rules is applied. Starting at the top (n=1) and working downwards

- If $Z(n)$ is estimated and $Z(n) > Z(n-1)$, then $Z(n) = Z(n-1)$
  i.e., If the current elevation is estimated and is above the elevation of the upper stratum, then reset it equal to the elevation of the upper stratum.

The logic also includes one final check working from the bottom upwards to ensure that there are no remaining overlaps.

The method for estimating strata elevations described above ensures that all 19 strata have elevations for each cell. The DTMs for each stratum are created from these elevations and so all DTMs extend over the full extent of the data (Figure 25.1). This set of DTMs is referred to as DTM1.

When DTM1 is created, the average Z co-ordinate for each triangle is calculated. This means that by comparing successive strata it is possible to identify where the thickness of a stratum is zero and then to remove that triangle. This will introduce holes into the DTMs where there are no data and where the thickness is zero. This new set of DTMs is referred to as DTM2 (Figure 25.2).

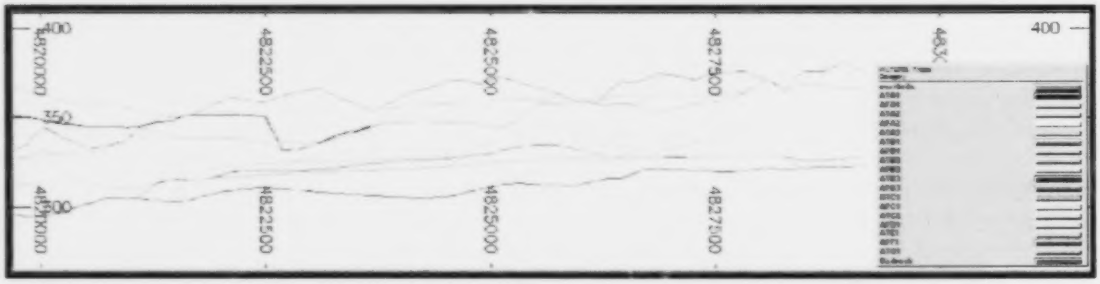
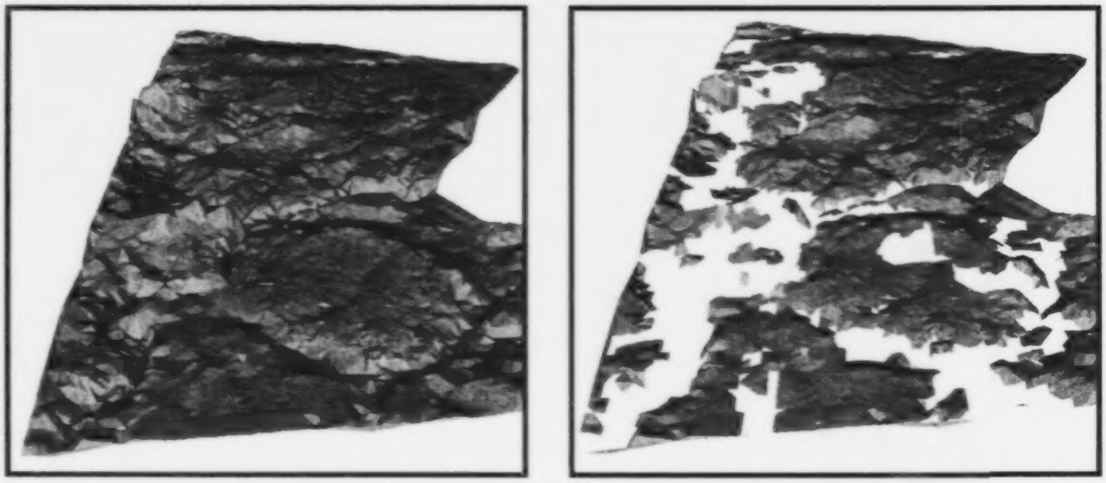


Figure 25.1. Section view of DTMs (wireframes) for a portion of the study area (vertical exaggeration 20X).



DTM1

DTM2

Figure 25.2. Perspective view of DTMs for aquitard surface ATB1. The left DTM shows the unit as a continuous surface with no gaps, whereas the one on the right has gaps where the unit is not present (vertical exaggeration 20X).

Creating Three-Dimensional Block Models

The block modelling techniques described so far have been used to interpolate elevations onto a 2D grid of irregular points corresponding to the X,Y co-ordinates of one or more picks. These points are at the centres of the model cells, but the actual dimensions of the cells are not used.

A 3D block model representing all strata is created by filling the space between each stratum in DTM1 with subcells (Figure 25.3). The planar dimensions of a subcell may be defined by the user, but it was decided that 200 m x 200 m provided a good resolution without creating too many cells—there are approximately 140 000 cells in the full model. The dimension of each subcell in the vertical direction is calculated automatically so that it fits exactly between the strata. The model created using this method is referred to as model 1.

A second model, model 2, is created in which all subcells are split along the horizontal planes corresponding to 10 m benches. Thus, the thicker strata will contain several full 10 m subcells plus both an upper and lower subcell of less than 10 m. The number of cells in this model is approximately 4 times that of model 1. The advantage of model 2 is that the subcells for an individual stratum can be displayed and coloured according to the elevation of each subcell.

Calculating Volumes and Grids

The volume of each stratum over the whole area or over a subset of the area can be calculated from either DTM1 or either model. The results are classified both by stratum and by aquifer–aquitard. Model 1 includes the co-ordinates of each subcell centre and the thickness of each subcell on a regular X–Y grid. Hence, the elevation of the top of each stratum can be calculated and exported as a text file, which can be used as input to other software packages for hydrogeological modelling or visualization.

CONCLUSIONS

The flexible and comprehensive database and modelling options available in Datamine Studio® have allowed a method to be created that follows a logic that is appropriate for the modelling of aquifers and aquitards. As is often the case in this type of study, the modelling steps are repeated many times during the course of a project as data are refined and corrected and interpretations change. The ability to put the entire model build behind a single button on a tailored interface has been a major contributor to the success of this project.

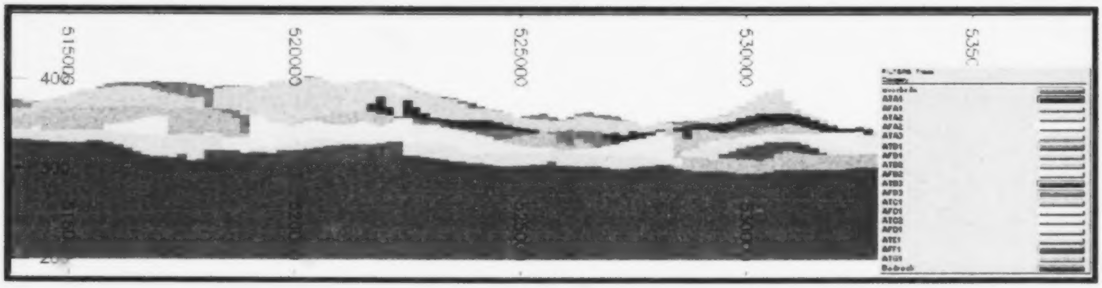


Figure 25.3. Section view of block model 1 created for a portion of the study area (vertical exaggeration 20X).

Using the above rules, it is still possible to have strata out of sequence and so a second set of rules is applied. Starting at the top (n=1) and working downwards

- If $Z(n)$ is estimated and $Z(n) > Z(n-1)$, then $Z(n) = Z(n-1)$
  i.e., If the current elevation is estimated and is above the elevation of the upper stratum, then reset it equal to the elevation of the upper stratum.

The logic also includes one final check working from the bottom upwards to ensure that there are no remaining overlaps.

The method for estimating strata elevations described above ensures that all 19 strata have elevations for each cell. The DTMs for each stratum are created from these elevations and so all DTMs extend over the full extent of the data (Figure 25.1). This set of DTMs is referred to as DTM1.

When DTM1 is created, the average Z co-ordinate for each triangle is calculated. This means that by comparing successive strata it is possible to identify where the thickness of a stratum is zero and then to remove that triangle. This will introduce holes into the DTMs where there are no data and where the thickness is zero. This new set of DTMs is referred to as DTM2 (Figure 25.2).

Figure 25.1. Section view of DTMs (wireframes) for a portion of the study area (vertical exaggeration 20X).

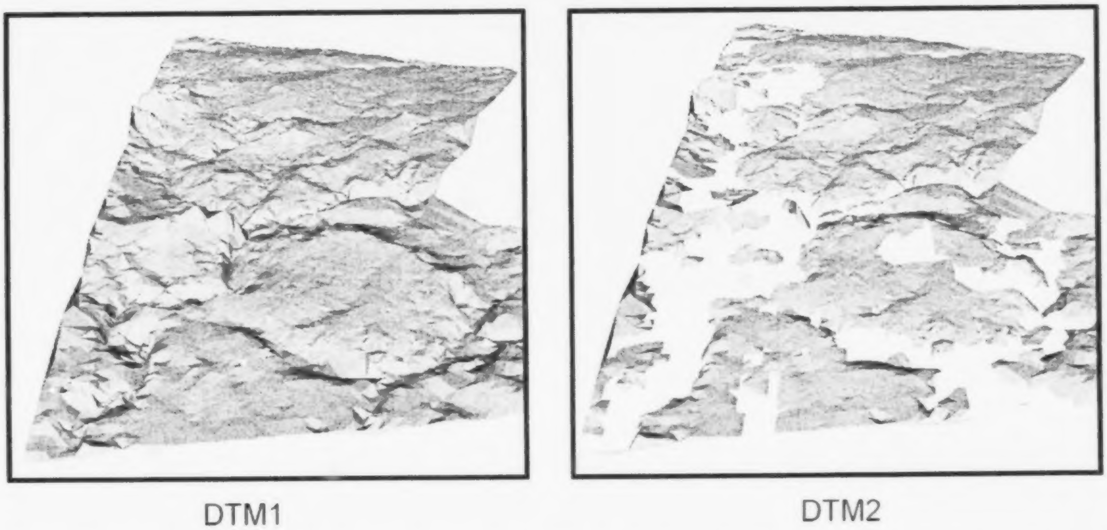


Figure 25.2. Perspective view of DTMs for aquitard surface A1B1. The left DTM shows the unit as a continuous surface with no gaps, whereas the one on the right has gaps where the unit is not present (vertical exaggeration 20X).

Creating Three-Dimensional Block Models

The block modelling techniques described so far have been used to interpolate elevations onto a 2D grid of irregular points corresponding to the X,Y co-ordinates of one or more picks. These points are at the centres of the model cells, but the actual dimensions of the cells are not used.

A 3D block model representing all strata is created by filling the space between each stratum in DTM1 with subcells (Figure 25.3). The planar dimensions of a subcell may be defined by the user, but it was decided that 200 m × 200 m provided a good resolution without creating too many cells—there are approximately 140 000 cells in the full model. The dimension of each subcell in the vertical direction is calculated automatically so that it fits exactly between the strata. The model created using this method is referred to as model 1.

A second model, model 2, is created in which all subcells are split along the horizontal planes corresponding to 10 m benches. Thus, the thicker strata will contain several full 10 m subcells plus both an upper and lower subcell of less than 10 m. The number of cells in this model is approximately 4 times that of model 1. The advantage of model 2 is that the subcells for an individual stratum can be displayed and coloured according to the elevation of each subcell.

Calculating Volumes and Grids

The volume of each stratum over the whole area or over a subset of the area can be calculated from either DTM1 or either model. The results are classified both by stratum and by aquifer–aquitard. Model 1 includes the co-ordinates of each subcell centre and the thickness of each subcell on a regular X–Y grid. Hence, the elevation of the top of each stratum can be calculated and exported as a text file, which can be used as input to other software packages for hydrogeological modelling or visualization.

CONCLUSIONS

The flexible and comprehensive database and modelling options available in Datamine Studio® have allowed a method to be created that follows a logic that is appropriate for the modelling of aquifers and aquitards. As is often the case in this type of study, the modelling steps are repeated many times during the course of a project as data are refined and corrected and interpretations change. The ability to put the entire model build behind a single button on a tailored interface has been a major contributor to the success of this project.

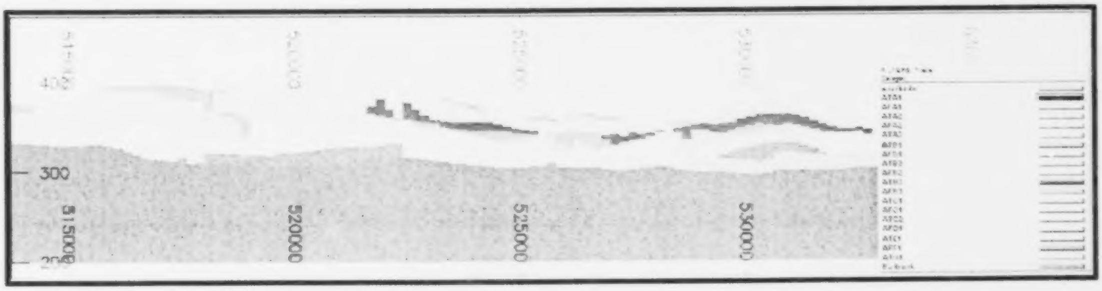


Figure 25.3. Section view of block model 1 created for a portion of the study area (vertical exaggeration 20X).

The high-quality 3D visualization and display options allow the different data types (boreholes, points, wireframes, block models) to be selectively displayed and manipulated. This greatly facilitates the validation of the base data from which the models are created. The ability to easily select subsets of the project area and create models for these subareas means that the models can be created in a matter of minutes, which makes it a very practical tool for regular use. Few changes would be required to apply the system to other similar project areas.

Following the construction of the three-dimensional geologic model for Waterloo Region, activities will shift and focus on the development of both technical and "user-friendly" derivative products that will assist with policy-making decisions and resolution of land use issues. Those products generated for the non-technical user must be in a format that is easily understood and interpreted to maximize value.

REFERENCES

Bajc, A.F. 2002. Mapping the subsurface of Waterloo Region; *in* Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.31-1 to 31-6.

——— 2004. Three-dimensional mapping of Quaternary deposits in Waterloo Region, southwestern Ontario; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.24-1 to 24-4.

Bajc, A.F., Endres, A.L., Hunter, J.A. and Pullan, S.E. 2003. An update on three-dimensional mapping of Quaternary deposits in Waterloo region, southwestern Ontario; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.24-1 to 24-7.

Bajc, A.F. and Karrow, P.F. 2004. 3-dimensional mapping of Quaternary deposits in the Regional Municipality of Waterloo, southwestern Ontario: Geological Association of Canada, Annual Meeting, St. Catharines, Ontario, Fieldtrip Guidebook FT-7, 72p.

Hansel, A.K., Stiff, B.J. and Barnhardt, M.L. 2004. Three-dimensional geologic mapping in rapid-growth areas: a case study from Lake County, Northeastern Illinois; Illinois State Geological Survey, Open File-Series 2004-8, p.23-27.

Logan, C., Russell, H., Sharpe, D. and Kenny, F., in press. The role of expert knowledge, GIS and geospatial data management in a basin analysis, Oak Ridges Moraine, southern Ontario; *in* GIS Application in the Earth Sciences, Geological Association of Canada, Special Paper.

O'Connor, D.R. 2002. Report of the Walkerton Inquiry; the events of May 2000 and related issues; Ontario Ministry of the Attorney General, Toronto, Ontario, Parts 1 and 2, 1280p.

26. Project Unit 03-021. Three-Dimensional Modelling of Thick Quaternary Deposits in the Barrie Area, Central Ontario

A.K. Burt[1] and D.F. Russell[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Groundwater is a critical resource for many of Ontario's residents. In recent years, the recognition of the need to protect existing groundwater resources has increased substantially. Numerous pieces of legislation have been or are being introduced that focus on the protection and utilization of the provinces groundwater resources. Identification of groundwater aquifers is an important component of any protection or identification initiative.

A critical component of mapping groundwater aquifers is a thorough understanding of the three-dimensional stratigraphy of Quaternary (surficial) sediments. These sediments form recharge and discharge zones, local and regional aquitards and aquifers. Accurate three-dimensional models will allow new aquifers to be located and the estimation of volume of groundwater resources. Of equal importance, the models can be used to identify potential pathways for aquifer contamination.

This report provides an update of a multi-year project aimed at the construction of a three-dimensional geologic model of Quaternary sediments in the Barrie area (Burt 2004; Slattery 2003). The model will be based on new drilling and associated downhole geophysics, new seismic surveys, pre-existing drilling logs, water well records, published surficial maps and the interpretation of natural and man-made exposures (Figure 26.1).

LOCATION

The study area encompasses approximately 1200 km^2 between Georgian Bay and Lake Simcoe, and is centred on the Oro Moraine (also referred to as Bass Lake kame moraine, Oro sandhills) located north of the City of Barrie (*see* Figure 26.1). Portions of 3 townships, Oro–Medonte, Severn and Springwater, represented on 1:50 000 scale NTS map sheets 31 D/5, 31 D/6, 31 D/11 and 31 D/12, are included within the study area. The metropolitan areas of Barrie, on Kempenfelt Bay (Lake Simcoe), and Orillia, on Lake Couchiching, are the largest urban centres within the study area and have a combined population of nearly 200 000.

Lake Couchiching, in the northeast, and Lake Simcoe, in the south and east, form natural boundaries to the study area. Smaller lakes found within the study area include Bass Lake, Little Lake and Orr Lake. Southeast of the moraine, surface water drains into Lake Simcoe; southwest, the moraine drains into Lake Huron; and north and northwest of the moraine, it drains into Georgian Bay through Severn Sound.

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.26-1 to 26-9.

© Queen's Printer for Ontario, 2005

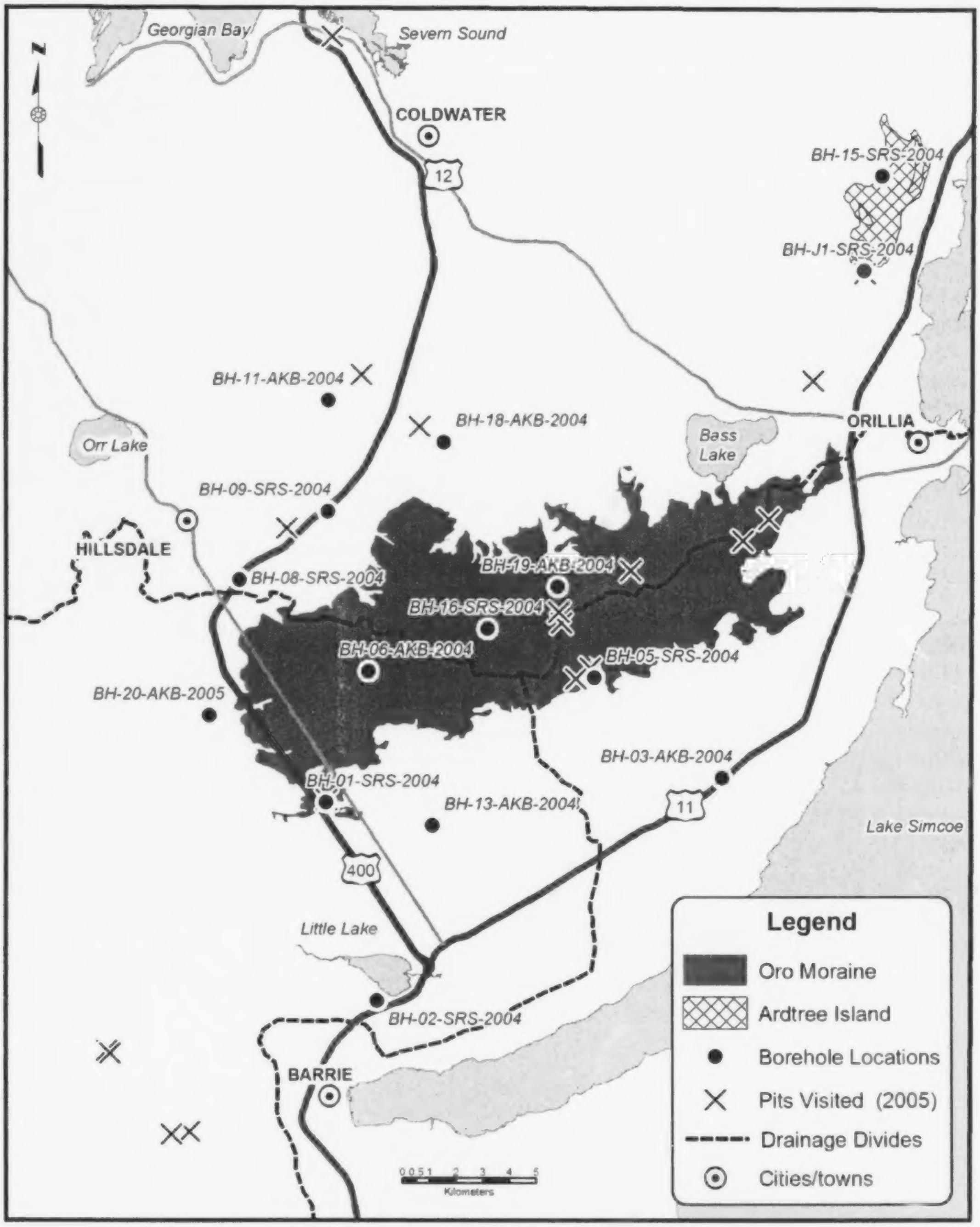

Georgian Bay
Severn Sound
N
COLDWATER
12
BH-15-SRS-2004
BH-J1-SRS-2004
BH-11-AKB-2004
BH-18-AKB-2004
Orr Lake
Bass Lake
ORILLIA
BH-09-SRS-2004
HILLSDALE
BH-08-SRS-2004
BH-19-AKB-2004
BH-16-SRS-2004
BH-06-AKB-2004
BH-05-SRS-2004
BH-20-AKB-2005
BH-03-AKB-2004
BH-01-SRS-2004
BH-13-AKB-2004
11
Lake Simcoe
400
Little Lake
BH-02-SRS-2004
BARRIE
0 0.5 1 2 3 4 5
Kilometers
Legend
Oro Moraine
Ardtree Island
Borehole Locations
Pits Visited (2005)
Drainage Divides
Cities/towns

Figure 26.1. Location and boundary of the study area. The Oro Moraine, shown in dark grey, is the most prominent landform within the study area. Boreholes completed in 2004 and early 2005 are indicated.

BEDROCK GEOLOGY

Exposures of bedrock in the study area are limited in extent and are confined to a narrow east-trending band across the northern boundary. Outcrops straddle the Black River Escarpment, which represents the contact between older Proterozoic-age rocks of the Grenville Province to the north and Middle Ordovician-age rocks to the south.

Rocks of the Grenville Province consist of layered biotite gneiss and migmatite, quartzofeldspathic gneiss, orthogneiss and paragneiss around the northern tip of Lake Couchiching. Westward toward Georgian Bay, the rocks consist of tonalite, granodiorite, monzonite, granite, syenite and derived gneisses. Exposures occur along roads and in fields, where rounded knobs protrude through flat-lying surficial sediments (Photo 26.1).

The bedrock geology of the study area is dominated by rocks of Middle Ordovician age (Liberty 1969). The lowermost unit, the Shadow Lake Formation, is composed of interbedded siliciclastic shale and sandstone, and unconformably overlies the Proterozoic basement rocks. Overlying the Shadow Lake Formation is the Gull River Formation, a generally fine- to very fine-grained to argillaceous, sparsely to locally very fossiliferous, thin- to medium-bedded limestone. The Bobcaygeon Formation overlies the Gull River, and is composed of fine- to coarse-grained, moderately fossiliferous, irregular- to medium-thick-bedded limestone with calcareous shale partings and interbeds in the upper members. The uppermost unit in the area is the Verulam Formation, a medium- to coarse-grained bioclastic limestone with calcareous shale partings in the lower member.

QUATERNARY GEOLOGY

The sediments and landforms seen across the study area are the result glacial advances and retreats during the Late Wisconsinan Substage. The Lake Simcoe lobe covered the study area during the Port Bruce Stade and most likely deposited 3 of the 4 till units present in the study area. The lowermost till, which is rarely exposed, is the stony sandy silt to silt Bogarttown Till (Gwyn 1972). This is overlain by an unnamed stony sandy till (informally referred to as 'Northern Till') and the calcareous silt to sandy silt Newmarket Till (Barnett 1992, 1997; Gwyn 1972). The study area was ice free during the Mackinaw Interstade, circa 13 300 years BP (Dreimanis 1977). Subsequent Lake Simcoe Lobe ice advances during the Port Huron Stade, circa 13 000 years BP, deposited the highly calcareous silty clay to clay Kettleby Till (Gwyn 1972).

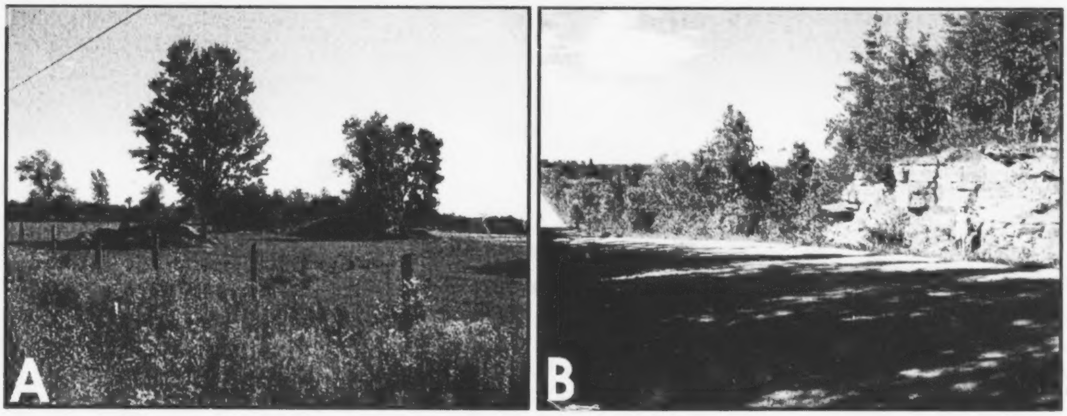


Photo 26.1. A) Rounded Precambrian bedrock knobs protruding through fine-grained glaciolacustrine sediments. B) Black River Escarpment.

The 'Northern' and Newmarket tills, which blanket the Simcoe Uplands (Chapman and Putnam 1984), are the most extensive surficial deposits throughout the south and northwest portions of the study area. The till surfaces are typically gently to steeply rolling to streamlined and are locally overlain by fine- to coarse-grained glaciolacustrine and outwash deposits. Modern streams bisect the till surface. The till exposures become smaller and increasingly streamlined moving north and east from the moraine. The only mapped exposures of Kettleby Till that fall within the study area are located above the Main Algonquin shoreline adjacent to Lake Simcoe and overlying a small upland feature in the far north of the study area (OGS 2003). The Bogarttown Till is not mapped at surface within the study area.

During the summer and fall of 2004, a series of boreholes (BH-03-AKB-2004, BH-11-AKB-2004 and BH-13-AKB-2004) were drilled into the Simcoe Uplands (*see* Figure 26.1 for borehole locations). Borehole BH-03-AKB-2004 reached bedrock at 106 m, whereas BH-11-AKB-2004 and BH-13-AKB-2004 were drilled to depths greater than 110 m, but did not reach bedrock. In all 3 boreholes, a series of silty and sandy till units were separated by fine-grained outwash deposits and thick, often rhythmically bedded glaciolacustrine fine sand, silt and clay with thin debris flow units. The presence of glaciolacustrine sediments interbedded with till indicates that ponding of meltwater occurred in association with each advance and retreat of the Simcoe Lobe. Paleoflow measurements taken at a roadcut exposure from a rippled sand unit overlain by stony sandy 'Northern till' record dominantly south to slightly southwest flow directions. These paleoflow measurements support the interpretation of a Simcoe Lobe source for the sediment and water.

The most prominent feature of the study area is the approximately 165 km^2 Oro Moraine, which extends from Bass Lake westward to Highway 400 (*see* Figure 26.1). This upland feature has numerous local topographic highs with deeply incised hummocky surfaces. The Oro Moraine has been interpreted as an end moraine formed during a standstill of the Lake Simcoe lobe (Deane 1950); as an interlobate moraine overridden by ice from the Lake Simcoe basin (Gravenor 1957); as a remnant deposit of an earlier sandy moraine built by the Georgian Bay lobe that was subsequently overridden from the northeast (Chapman and Putnam 1984); as an interlobate feature deposited as a series of coalescing subaqueous fans (Barnett 1986, 1989); and as a series of stacked subaqueous fans (Slattery 2003).

Sand and gravel pits across the moraine were investigated during the 2003 field season (Slattery 2003) with supplementary observations made during the 2005 field season (Photo 26.2). Detailed descriptions of channel and interchannel sediments from upper to distal fan locations may be found in Slattery (2003). Dominantly south to southwest paleoflow directions and Precambrian lithologies in the gravel suggest a predominantly northeastern sediment source for the moraine. In this model, the moraine is viewed as a late glacial feature that postdates deposition of the 'Northern' and Newmarket tills. This model is somewhat different from that proposed by Barnett (1989). Barnett (1989) proposed that the

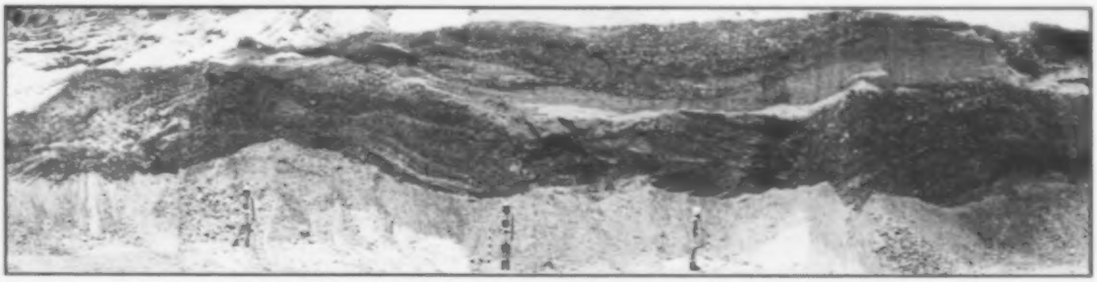


Photo 26.2. Proximal to midfan channel sand and gravel and interchannel sand overlain by distal fan fine-textured sand in upper left of figure.

main supply of sediment to the moraine was from glacial ice on the south side, located within Lake Simcoe. According Barnett's model, sediment was fed to the moraine via 2 main conduits, one at the east end of the moraine and the second on the southern side. Sediments were deposited in the interlobate zone as subaqueous fans and within open and closed conduits. Barnett (1989) suggests that 3 main stages of moraine formation occurred as the interlobate zone widened.

Boreholes BH-06-AKB-2004 and BH-16-SRS-2004 were drilled in the western and central regions of the moraine and, in each case, ceased in dry sand 69 m and 72 m, respectively, below surface. Borehole BH-06-AKB-2004 is dominated by fining-upward sequences of gravelly sand and sand interbedded with thin silty and sandy diamicton units. The fining-upward sequences are interpreted as channel and interchannel sediments that were likely deposited in an upper to mid-subaqueous fan location. The thin diamicton units are interpreted as debris flow deposits. Borehole BH-16-SRS-2004 intersects a 12 m thick silty sand diamicton unit interpreted as Newmarket till. This till is overlain by nearly 30 m of silty sand, sand and gravelly sand interbedded with thin debris flow diamicton units. These sediments may have been deposited in mid to distal subaqueous fan locations. The lower 30 m of the hole is dominated by fine-grained glaciolacustrine or distal outwash deposits.

The complex stratigraphic interrelationship of diamicton, fine- and coarse-grained glaciolacustrine sediments, subaqueous outwash fan sediments and fluvial sediments at the edges of the moraine is most clearly seen in a pit located at the far southwestern corner of the moraine. Small test pits dug in the floor of the main excavation reveal fine-grained diamicton and glaciolacustrine clay with abundant dropstones. These sediments are overlain by thick sand beds with minor gravelly sand and gravel. Paleoflow measurements from these deposits indicate flow directions to the southwest and southeast. The thick sands are overlain by a stony, sandy till (Photo 26.3), which, in turn, is overlain by laminated silt and clay-rich glaciolacustrine sediments. The uppermost units are a thin stratified diamict, interpreted as a debris flow, and finally channel sands.

The complex nature of the moraine margin deposits at depth are revealed in boreholes BH-01-SRS-2004, BH-05-SRS-2004 and BH-19-AKB-2004, drilled at or near the edges of the moraine. Borehole BH-01-SRS-2004 reached bedrock at 95 m below surface, whereas BH-05-SRS-2004 and BH-19-AKB-2004 were drilled to 110 m and 60 m, respectively, without reaching bedrock. The lower 50 m of BH-01-SRS-2004 is characterized by interbedded tills, glaciolacustrine and possible outwash deposits similar to the till uplands, whereas the upper 45 m is dominantly sand and gravel interpreted as proximal to upper subaqueous fan sediments. Boreholes BH-05-SRS-2004 and BH-19-AKB-2004 are characterized at depth by thick glaciolacustrine fine-textured sands, silts and clays interbedded with till (BH-05-SRS-2004) and nearshore or outwash sands overlain by upper to mid (BH-05-SRS-2004) and distal (BH-19-AKB-2004) fan deposits interbedded with till and/or debris flow diamicton units.

A hypothesis that Ardtree island, a small till upland located north of Orillia, represents a northern extension of the Oro Moraine, was explored in BH-15-SRS-2004, a borehole drilled on the western flank of the upland. The borehole reached bedrock at 39 m. This shallower depth, as compared to other upland boreholes, is expected as bedrock crops out north of the borehole. The base of the hole is characterized by a thin sandy diamicton unit overlain by 2.5 m of gravelly sand. The upper 35 m of sediments include glaciolacustrine fine-textured sands, silts and clays interbedded with multiple diamicton units. These sediments are comparable to those encountered in boreholes BH-03-AKB-2005, BH-13-AKB-2005 and BH-11-AKB-2005, which were drilled in the main part of the uplands, rather than the coarser textured sand and gravels that would be anticipated for a northern extension of the moraine.

The most prominent features on the western side of the study area are a series of broad, flat-bottomed and steep-sided valleys incised by underfit modern streams and frequently containing lakes and wetlands (Photo 26.4). The city of Barrie currently exploits groundwater within one of these valleys for its municipal supply. To date, 4 boreholes have been drilled in the valley systems. Boreholes BH-08-SRS-2004, BH-09-SRS-2004 and BH-20-AKB-2005 record sediment thicknesses near or exceeding 100 m, whereas the 65 m deep borehole BH-18-AKB-2004 records the rise in bedrock to the north. Boreholes BH-08-SRS-2004, BH-09-SRS-2004 and BH-18-AKB-2004 each have thin diamicton units directly overlying bedrock that likely represent pre-existing basal sediments eroded by the later meltwater events. Borehole BH-18-AKB-2004 coarsens upwards from deeper water glaciolacustrine laminated to thinly-bedded fine-textured sands, silts and clays to shallower fine- to medium-grained sands, whereas borehole BH-20-AKB-2005 is dominated by laminated to thinly bedded silts and fine-textured sands with clay laminations. Boreholes BH-08-SRS-2004 and BH-09-SRS-2004 were drilled at the edges of the valleys and have more complex geology. Borehole BH-08-SRS-2004 consists of over 45 m of glaciolacustrine silts and clays overlain by dominantly sands and gravels with multiple thin debris flow diamicton units. Borehole BH-09-SRS-2004 is dominated by silts and fine- to medium-grained sands with thin pulses of coarser gravel interbedded with diamicton. Coarser sands and gravels interbedded with thin clays are common in the upper 35 m of the borehole. These boreholes have yet to be fully interpreted, but may include sediments slumped off the nearby uplands.

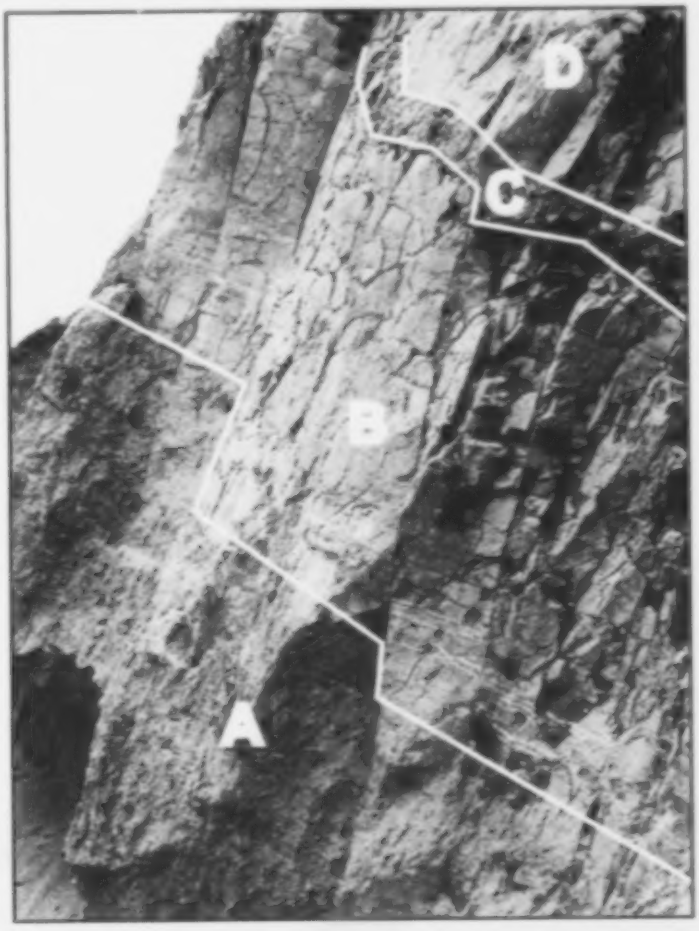


Photo 26.3. Stony, sandy till (A) overlain by laminated silt and clay-rich glaciolacustrine sediments (B) overlain by a thin stratified debris flow diamict (C) and finally channel sands (D). The section pictured here is faulted.

Theories on the mechanism of formation of the large valley systems in the study area have previously been put forward. These theories include subaerial erosion prior to the last glaciation, tunnel valleys formed by rapid meltwater release (Barnett 1986, 1989), or the presence of late-stage ice tongues (Deane 1950). Many of the valleys in the study area are oriented north-northeast to northeast, subparallel to re-entrant bedrock valleys observed along the Paleozoic–Proterozoic boundary to the east of Lake Simcoe, as well as further west at the Niagara Escarpment and along the Bruce Peninsula. These observed valleys are, in turn, aligned with regional bedrock joint orientations. Given the occurrence of re-entrant bedrock valleys to the east and west, it is anticipated that the valleys also occur at the northern edge of the study area. At present, their extent beneath the sedimentary cover is not known, nor is their influence on the formation of the valleys in the study area. It is hoped that results from the current drilling program will help to resolve these questions.

Glacial outwash deposits, fine-grained glaciolacustrine sediments and glaciolacustrine beaches and bars were deposited in glacial Lake Algonquin after glacial ice had withdrawn from the area. These deposits were observed in shallow roadcuts and ditches across the northern portion of the study area. The majority of shoreline features within the study area are related to the main level of glacial Lake Algonquin. Higher level shoreline features may be related to early glacial Lake Algonquin or glacial Lake Schomberg (Finamore 1981; Finamore and Bajc 1984; Chapman and Putnam 1984; Barnett 1988, 1997). A natural exposure north of Bass Lake records over 7 m of deep-water laminated silts and clays overlain by shallower water silty, very fine-textured sand and, finally, 2 to 2.5 m of sand and gravel, which are interpreted as beach deposits.

Postglacial deposits are limited within the study area. Organic deposits consisting of peat, muck and marl are found in low-lying areas typically adjacent to lakes and in wetlands. There are also organic deposits overlying glaciolacustrine clay in some tunnel-channels likely in areas of groundwater discharge. Modern alluvium is found in generally narrow bands along the floodplains of many streams. Recent lacustrine silt and clay sediments are found in the lowlands adjacent to Severn Sound.

Photo 26.4. View from the base of a flat-bottomed valley to the upland area beyond.

PROJECT STATUS

Field work completed to date includes drilling, geophysical surveys and the description of pits and natural exposures. During the 2004 field season, 14 sonic boreholes (*see* Figure 26.1), totalling 1185 m, were drilled, logged in the field and sampled for carbonate content and grain size analysis. Two and one-half inch monitoring wells with 1.5 m screens have been installed by the Lake Simcoe Conservation Authority at selected boreholes. The results of the 2004 drilling program will be published by the Ontario Geological Survey in an upcoming Miscellaneous Release—Data (MRD). A similar number of mud rotary boreholes will be drilled in the fall of 2005. These holes will target the east half of the moraine, the till uplands south, west and north of the moraine and selected valleys west and north of the moraine. Monitoring wells will be installed where suitable aquifers are encountered.

Six seismic surveys, each approximately 1 km long, have been completed under contract by a geophysical company and the results are currently being processed. The Geological Survey of Canada (GSC) also completed a total of 7.5 km of seismic line during the summer of 2004 using its Mini Vibe system. Downhole geophysics were completed by the GSC and a contracted geophysical company in 2004 and early 2005. The geophysical information is being interpreted by a graduate student as part of a Masters degree.

REFERENCES

Barnett, P.J. 1986. Quaternary geology of the eastern halves of the Barrie and Elmvale areas, Simcoe County; *in* Summary of Field Work and Other Activities 1986, Ontario Geological Survey, Miscellaneous Paper 132, p.193-194.

——— 1988. Quaternary geology of the eastern half of the Elmvale area, Simcoe County; *in* Summary of Field Work and Other Activities 1988, Ontario Geological Survey, Miscellaneous Paper 141, p.405-406.

——— 1989. Quaternary geology of the Barrie and Elmvale area; *in* Summary of Field Work and Other Activites 1989; Ontario Geological Survey, Miscellaneous Paper 146, p.205-206.

——— 1992. Quaternary geology of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.1011-1088.

——— 1997. Quaternary geology, eastern half of the Barrie and Elmvale areas; Ontario Geological Survey, Map 2645, scale 1:50 000.

Burt, A.K. 2004. Three-dimensional mapping of Quaternary (surficial) deposits in the Barrie area, central Ontario; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.35-1 to 35-5.

Chapman, L.J. and Putnam, D.F. 1984. The physiography of southern Ontario; Ontario Geological Survey, Special Volume 2, 270p.

Deane, R.E. 1950. Pleistocene geology of the Lake Simcoe district, Ontario; Geological Survey of Canada, Memoir 256, 108p.

Dreimanis, A. 1977. Late Wisconsinan glacial retreat in the Great Lakes region, North America; Annals of New York Academy of Sciences, v.288, p.70-89.

Finamore, P.F. 1981. Quaternary geology of the Orillia area (31 D/11), Victoria and Simcoe counties, southern Ontario, *in* Summary of Field Work 1981, Ontario Geological Survey, Miscellaneous Paper 100, p.111-113.

Finamore, P.F. and Bajc, A.F. 1984. Quaternary geology of the Orillia area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2697, scale 1:50 000.

Gravenor, C.P. 1957. Surficial geology of the Lindsay–Peterborough area, Ontario, Victoria, Peterborough, Durham and Northumberland counties, Ontario; Geological Survey of Canada, Memoir 288, 60p.

Gwyn, Q.H.L. 1972. Quaternary geology of the Alliston–Newmarket area, southern Ontario; Ontario Division of Mines, Miscellaneous Paper 53, p.144-147.

Liberty, B.A. 1969. Paleozoic geology of the Lake Simcoe area, Ontario; Geological Survey of Canada, Memoir 355, 201p.

Ontario Geological Survey 2003. Surficial geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 128, v.1 and v.2.

Slattery, S.R. 2003. Subsurface mapping of the Barrie area, central Ontario; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.25-1 to 25-8.

27. Project Unit 05-012. Karst in Southern Ontario

F.R. Brunton[1], J.E.P. Dodge[1] and J. Shirota[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) has initiated a comprehensive study of karst features throughout southern Ontario, focussing on, but not limited to, those regions that possess both exposed and thinly buried sedimentary bedrock of Paleozoic age. This region encompasses the western edge of the central St. Lawrence Lowlands (southeastern Ontario) and the western St. Lawrence Lowlands (Chapman and Putnam 1984; Sanford 1993), including Manitoulin and adjacent islands (Figure 27.1). Karst features in Proterozoic-age marbles of the Grenville Geologic Province, and in particular, those proximal to the Proterozoic–Paleozoic unconformity, are also being investigated. This regional-scale survey of karst will incorporate and build upon currently active and past local and regionally based karst studies in southern Ontario (e.g., Ford 1961, 1983; Pluhar and Ford 1970; Ford and Quinlan 1973; Cowell and Ford 1975, 1980, 1983; Cowell and Woerns 1977; Goodchild 1978, 1984; Ford and Williams 1989; Cowell and Associates, Inc. 1989; Tinkler and Stenson 1992; Cowell et al. 1994; Worthington, Ford and Beddows 2000; Worthington 2003; Kunert and Coniglio 2002; Buck, Worthington and Ford 2003; Strynatka 2003; Russell 2004; Abbey, Hurley and Merry 2004).

The majority of published karst studies in Ontario have focussed on the Niagara Escarpment region, despite the fact that the longest and most areally extensive and accessible cave networks occur within Ordovician limestones of south-central and eastern Ontario (Ongley 1965; Gordon 2005). The Middle Devonian-age limestones within Huron and Bruce counties display significant sinkhole development, evidence of disappearing streams and underground streams, water wells that breathe (i.e., allow gas and water exchange from surface), and other hydrogeologic evidence suggesting laterally extensive and deeper karst (up to 100 m or more). Unfortunately, the significant overburden cover throughout much of southwestern Ontario makes it difficult to assess the true regional extent of this significant karst terrain.

The main purpose of this multi-year karst inventory project is to provide a geological framework and characterization of the physical-chemical responses of the various Paleozoic-age bedrock units throughout southern Ontario to karstification. It builds upon recent field studies carried out by OGS staff, the purposes of which were to assess particular physical characteristics of soils and the nature of jointing within selected thin-drift and exposed limestone plains in southern Ontario (Andjelkovic and Cruden 1998; Strynatka 2003; Russell 2004). The karst inventory project includes 2 field-based components: 1) a two-year karst mapping initiative of south-central and southeastern Ontario (2005) and southwestern Ontario (2006); and 2) a contracted assessment of bedrock character beneath selected thin-drift areas within the various limestone plains of southern Ontario. Karst data will be incorporated into the GIS-based bedrock geology, topography, and subsurface contour maps currently being produced by the Sedimentary Geoscience Section of the Ontario Geological Survey (see Dodge, Armstrong and Kelly, this volume; Shirota, Brunton and Kelly, this volume). Such data will assist client groups concerned with source water protection, nutrient management, cave conservation and heritage, and land-use planning initiatives. It will also play an integral part in groundwater and surface water mapping and modelling, watershed characterization, and will lead to the creation of bedrock vulnerability and/or susceptibility maps for southern Ontario.

Summary of Field Work and Other Activities 2005
Ontario Geological Survey, Open File Report 6172, p.27-1 to 27-7.

© Queen's Printer for Ontario, 2005

KARST IN SOUTHERN ONTARIO

Karst is a term used to describe landscapes that display distinctive features resulting from chemical dissolution and precipitation of bedrock known as carbonates (e.g., limestone, dolostone, and marble), gypsum, and salt. Such landscapes are typified by a wide range of closed surface depressions, a well-developed underground drainage system, and a paucity of surface streams. The highly varied interactions among chemical, physical and biological processes have a broad range of geological effects including dissolution, precipitation, sedimentation, subterranean collapse and/or ground subsidence. Diagnostic features include sinkholes (dolines), sinking streams, karren, and caves and large springs resulting from solutional interactions of circulating groundwater, which may exit to entrenched effluent streams. All of these features are present across the St. Lawrence Lowlands region.

Karst terrain constitutes approximately 25% of the land surface of the Earth. Many populated regions on Earth are located in karst terrains because of their physical beauty and proximity to abundant resources such as oil and gas, minerals, limestone quarries, and abundant groundwater supplies. It is interesting that for a landscape covering more than 20% of the North American continent, "karst" is a term that is foreign to most Ontarians. The main reason for this is that much of the limestone plains throughout the western and central St. Lawrence Lowlands have had the surficial expressions of karst either removed by erosion during the various glacial events over the past few million years and/or are presently covered by thick gravel, sand, and clay (glacial drift) units largely of Wisconsinan age that were deposited during the

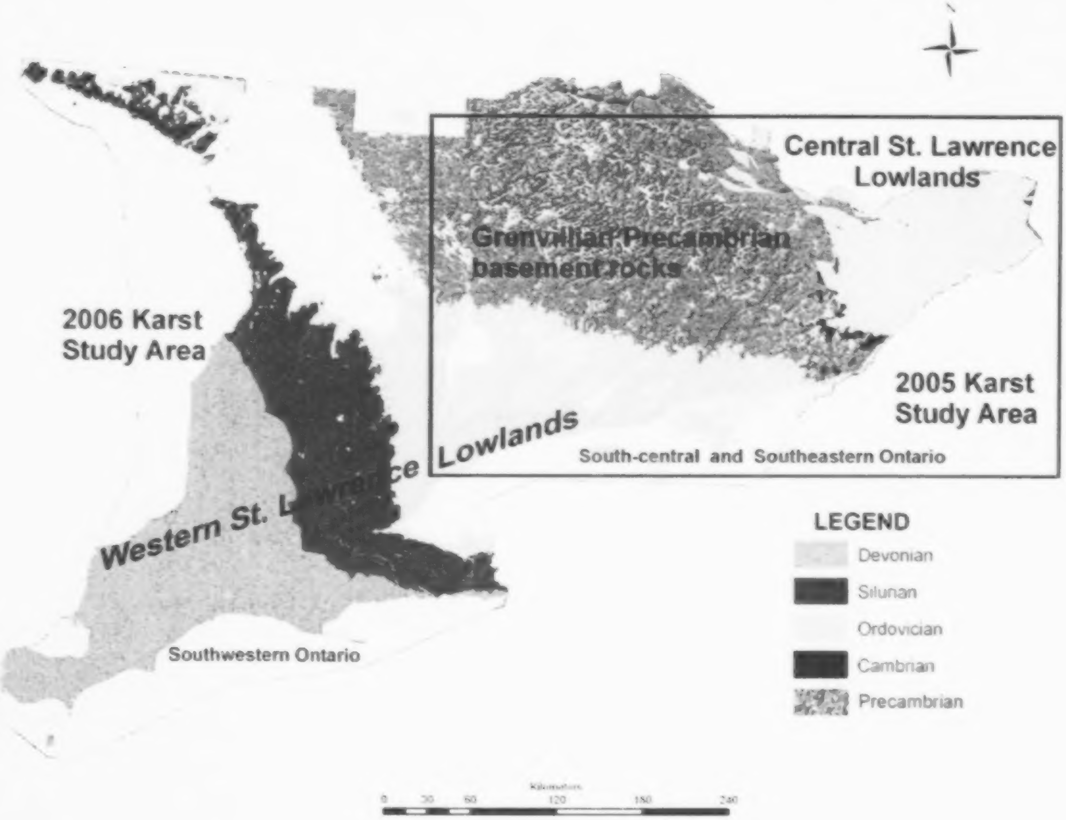

Central St. Lawrence Lowlands
Grenvillian Precambrian basement rocks
2006 Karst Study Area
2005 Karst Study Area
Western St. Lawrence Lowlands
South-central and Southeastern Ontario
Southwestern Ontario
LEGEND
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Kilometers
0
30
60
120
180
240

Figure 27.1. Location map showing karst study areas for 2005 (area within box) and 2006 (area outside of box) field seasons.

KARST IN SOUTHERN ONTARIO

Karst is a term used to describe landscapes that display distinctive features resulting from chemical dissolution and precipitation of bedrock known as carbonates (e.g., limestone, dolostone, and marble), gypsum, and salt. Such landscapes are typified by a wide range of closed surface depressions, a well-developed underground drainage system, and a paucity of surface streams. The highly varied interactions among chemical, physical and biological processes have a broad range of geological effects including dissolution, precipitation, sedimentation, subterranean collapse and/or ground subsidence. Diagnostic features include sinkholes (dolines), sinking streams, karren, and caves and large springs resulting from solutional interactions of circulating groundwater, which may exit to entrenched effluent streams. All of these features are present across the St. Lawrence Lowlands region.

Karst terrain constitutes approximately 25% of the land surface of the Earth. Many populated regions on Earth are located in karst terrains because of their physical beauty and proximity to abundant resources such as oil and gas, minerals, limestone quarries, and abundant groundwater supplies. It is interesting that for a landscape covering more than 20% of the North American continent, "karst" is a term that is foreign to most Ontarians. The main reason for this is that much of the limestone plains throughout the western and central St. Lawrence Lowlands have had the surficial expressions of karst either removed by erosion during the various glacial events over the past few million years and/or are presently covered by thick gravel, sand, and clay (glacial drift) units largely of Wisconsinan age that were deposited during the

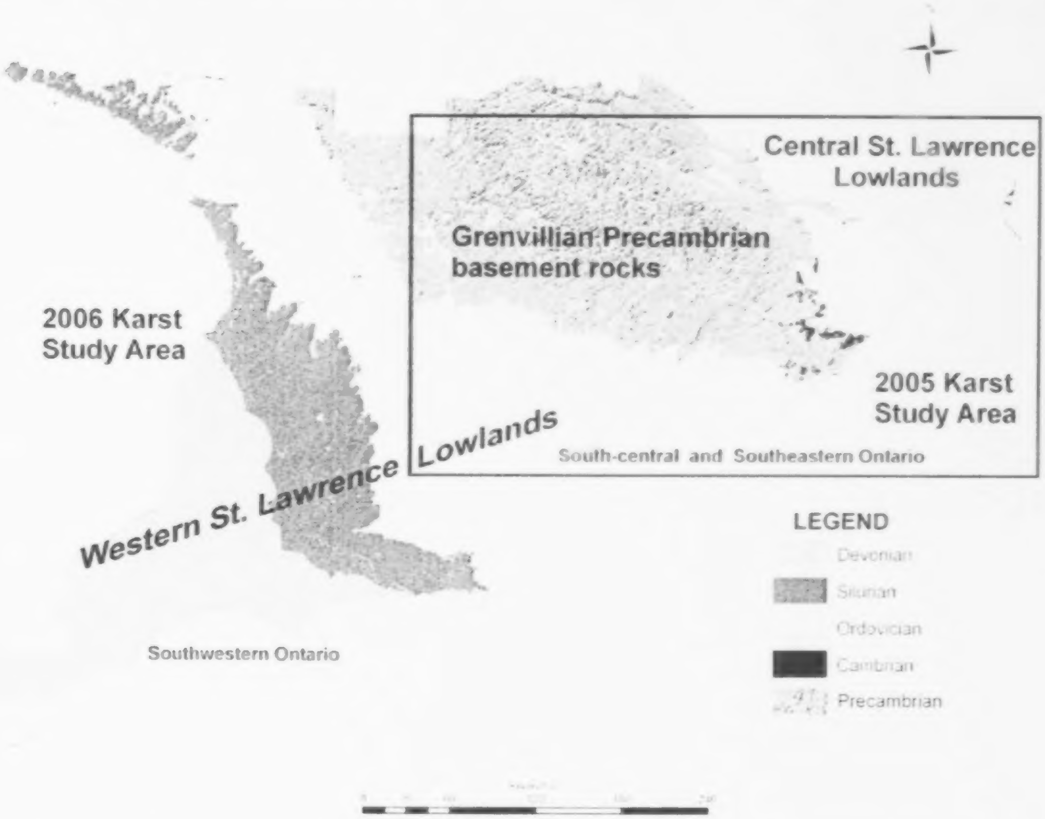

Central St. Lawrence Lowlands
Grenvillian Precambrian basement rocks
2006 Karst Study Area
2005 Karst Study Area
Western St. Lawrence Lowlands
South-central and Southeastern Ontario
Southwestern Ontario
LEGEND
Devonian
Silurian
Ordovician
Cambrian
Precambrian

Figure 27.1. Location map showing karst study areas for 2005 (area within box) and 2006 (area outside of box) field seasons.

retreat of the Laurentide Ice Sheet approximately 11 000 years ago (Barnett 1992). Such glacial deposits would have filled in and/or partially eroded surficial bedrock expressions of caves and sinkholes. At present, only select regions of exposed or thin drift limestone plains, representing about 10% of southern Ontario, allow for the nature of karstification to be described and interpreted. Extensive physical erosion of the bedrock surface also occurred during the last ice age, either through active abrasion by the moving ice and/or subsequent meltwater surges or flooding events that occurred during retreat of the ice lobes (e.g., Spencer 1890; Straw 1968; Karrow 1973; Barnett 1990; Shaw and Gilbert 1990; Kor, Shaw and Sharpe 1991; Brennard and Shaw 1994; Shaw 1996; Kor and Cowell 1998).

Karst landscapes are caused mainly by chemical erosion of bedrock by acidic surface and ground waters over a substantial time span—generally thousands to millions of years. Chemical leaching of these mainly sedimentary rocks creates enhanced permeability, especially along major joint sets in the upper tens of metres of exposed or thinly buried bedrock, resulting in conduit-style groundwater flow and greater connectivity between surface waters and groundwater aquifers. Therefore, shallow and, in some cases, even deeper groundwater aquifers in karsted terrains are more susceptible to biological and chemical contamination. Most of this underground water moves by laminar flow within interconnected narrow fissures (fractured bedrock) commonly referred to as channels or conduits. When these channels become enlarged above, at or below the water table, they may form subsurface maze and/or crevice cave networks. The water flow within these larger open cavernous structures may become turbulent. It appears that once conduits are 1 mm in diameter or greater, they may become significant in the karstification process (Worthington 2001, 2002; Worthington, Davies and Ford 2000).

Caves contain a variety of dissolution features, sediments and speleothems (deposits with various forms and mineralogy, chiefly calcite), all of which may preserve a record of the geological and climatic history of the area. Karst deposits and landforms may persist for extraordinarily long times in relict caves and paleokarst—something that has not been thoroughly investigated in many areas of Ontario. The limestone-dolostone bedrock karst features of southern Ontario are generally regarded as immature, even though interconnected maze and crevice caves within the Ordovician carbonates exceed 6 to 10 km in length and are among some of the longest in Canada (cf. Ford and Quinlan 1973; Ford 1983; White 1988; Ford and Williams 1989; Palmer 1991; Gordon 2005). The Paleozoic bedrock geology of states such as Kentucky, home of the Mammoth Caves, which are amongst the largest cave networks in North America, are very similar to Ontario; the main differences being that Kentucky was not glaciated, and the state's tectonic proximity to the various orogenic phases that formed the Appalachians.

PROJECT INITIATIVES AND PRELIMINARY OBSERVATIONS

Field projects associated with this two-year karst mapping initiative include 1) characterization of bedrock karst features, including documentation of site location; site description and photography; measurements of spacing and depth and strike of major joint sets; and, most importantly, general notes on lithologic units involved and geographic setting (i.e., location relative to key structural elements such as faults, folds and proximity to Precambrian basement inliers, mini-cuesta or escarpment margins, and other key physiographic features such as swamps, beaver ponds, streams, and position relative to paleodrainage areas, which are prime sources of acidified waters); and 2) a three-dimensional (3D) assessment of karsted carbonate bedrock sites within the various limestone plains in order to assess the vertical extent of karst and potential fluid pathways at depth.

Karst mapping during the 2005 field season focussed mainly in the Ordovician limestone plains of south-central and southeastern Ontario. Reconnaissance-level field mapping and core logging were also undertaken in two key karst regions: 1) those regions of Huron and Essex counties underlain by Middle Devonian limestones, which represent a significant karst terrain; and 2) along the Niagara Escarpment, where Silurian-age dolostone caprock displays significant karstification and glacial sculpting resulting in the beautiful vistas of the Bruce Peninsula and Manitoulin Island.

Consultations and discussions with numerous land owners, staff of various Conservation Authorities, karst geologists, and cavers has resulted in the compilation of more than 400 caves and other karst features, such as sinkholes, throughout southern Ontario. Field investigations of many of the more significant features have revealed some interesting regionally significant relationships. Almost all of the Ordovician limestone units display good joint-set development and variable degrees of dissolution at particular locations in the study area. Some of the major joints can persist through tens of metres of bedrock and extend from one formation to the next. However, cave development is largely restricted to the Gull River Formation. The main controls on cave formation appear to be 1) proximity to the region along which the Paleozoic–Precambrian unconformity spans; 2) proximity to major river systems and adjacent swampy areas; and 3) proximity to margins of mini-escarpments or cuestas between the major rivers (i.e., situated at inferred margins of paleodrainage systems). Often, the caves are larger and joint-controlled passageways are better developed where the Bobcaygeon Formation forms a thin caprock on the Gull River Formation.

Cave investigations to date have not uncovered deposits (speleothems in form of stalactites and flowstone) or physical attributes that are older than the last glacial phase (i.e., 11 000 years BP). Future investigations may reveal older deposits. Cave geometries appear to largely follow the regional joint patterns, and the Gull River Formation appears to be the most susceptible to joint dissolution. In part, this is due to the fact that most of the major rivers have incised downward into the Gull River Formation, enabling for sufficient volume and contact time with surface and ground waters to enable significant joint dissolution and the creation of substantive crevice- or maze-like caves. The longest reported cave

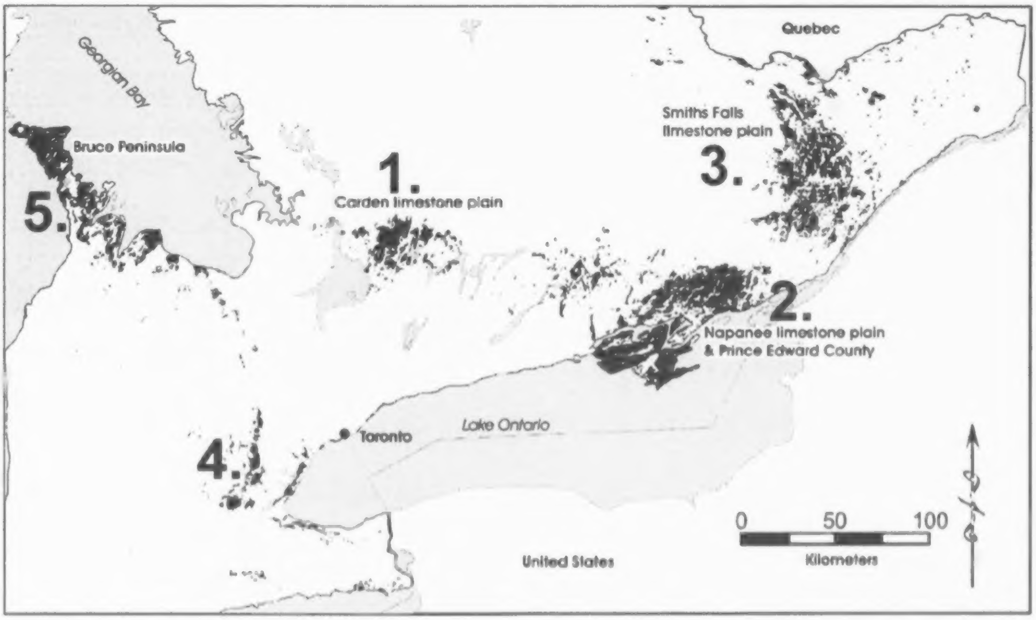


Figure 27.2. Locations and names of thin-drift limestone-dolostone plains (patchy shaded regions scattered throughout St. Lawrence Lowlands region) in southern Ontario, not including the extensive plains of Manitoulin and adjacent islands of the north shore of Lake Huron. The thin-drift regions, which constitute sedimentary bedrock that is covered by less than 1 m of overburden, represent only about 10% of the total area underlain by Paleozoic sedimentary rocks of the St. Lawrence Lowlands. The numbered regions (1–5) refer to broad areas where a 3D-bedrock field study will be carried out in fall of 2005.

networks in southern Ontario occur near Ottawa, along the Ottawa River, and possess more than 10 km of interconnected labyrinths. Some of the caves in and around the Belleville area also have upwards of 10 km of interconnected pathways, and possessing multiple entrances and resurgences.

The second project, which will be contracted out, involves a surface and subsurface (borehole) study of thin-drift or exposed Paleozoic bedrock plains within 5 regions of southern Ontario (Figure 27.2). The main purpose of the study is to assess "potential pathways" of surface waters and/or contaminants into Paleozoic bedrock. This project will add geological information in the third dimension in order to assist decision-makers in protecting the public well-being by assessing the relative vulnerability and/or susceptibility of bedrock in these thin-drift limestone plains.

Sedimentary Geoscience Section (SGS) staff have chosen 5 broad regions (study areas) from which specific field sites (a minimum of 5 sites per study area) will be selected and examined by the proponent. Within each study area, bedrock sites will be chosen that display a variety of responses to chemical and physical weathering and karstification. Therefore, the various sites within each study area will be selected to reflect the spectrum of bedrock surfaces from those displaying little response to fracturing and jointing to sites where the bedrock surface displays well-developed joint sets and cracks and/or solution-enhancement such as "clint" and "grike" formation or where open cavities are present.

The purpose of this site selection is to investigate whether the degree of surficial bedrock expressions of karstification, or lack of it, can be used to predict bedrock response in the subsurface (i.e., upper 10 to 30 m of bedrock). The 5 areas include

1. Middle Ordovician-age carbonates of the Carden limestone plain;
2. Middle Ordovician-age carbonates of the Napanee limestone plain and Prince Edward County;
3. Cambro-Ordovician-age carbonates of the Smiths Falls limestone plain, including the Ottawa region;
4. Early to Late Silurian-age dolostones (Amabel to Guelph formations) of the Guelph–Rockwood–Puslinch region to central Niagara Escarpment region; and
5. Wiarton area of the Bruce Peninsula–northern Niagara Escarpment region.

Caves and other karst features within the Silurian and Devonian carbonates of southwestern Ontario will be investigated in 2006 (*see* Figure 27.1). The GIS-based bedrock topography, geology, and subsurface map layers will all be used to assess regional structural, stratigraphic and geomorphological controls on karst development relative to what is evident in the thin-drift and exposed limestone and dolostone areas.

REFERENCES

Abbey, D., Hurley, J. and Merry, A.G. 2004. Sinkhole investigation in the Ausable Bayfield Conservation Authority watershed and surrounding area; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.29-1 to 29-6.

Andjelkovic, D. and Cruden, A.R. 1998. Relationships between fractures in Paleozoic cover rocks and structures in the Precambrian basement, south-central Ontario; *in* Summary of Field Work and Other Activities, Ontario Geological Survey, Miscellaneous Paper 169, p.275-280.

Barnett, P.J. 1990. Tunnel valleys: evidence of catastrophic release of subglacial meltwater, central-southern Ontario, Canada; Geological Society of America, Abstracts with Programs, v.22, no.7, p.48.

——— 1992. Quaternary geology of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.1011-1088.

Brennard, T.A. and Shaw, J. 1994. Tunnel channels and associated landforms, south-central Ontario: their implications for ice-sheet hydrology; Canadian Journal of Earth Sciences, v.31, p.505-522.

Buck, M.J., Worthington, S.R.H. and Ford, D.C. 2003. Earth science inventory and evaluation of the Eramosa karst area of natural and scientific interest; Ontario Ministry of Natural Resources, Guelph District, south-central Region, 51p.

Chapman, L.J. and Putnam, D.F. 1984. The physiography of southern Ontario, 3rd ed.; Ontario Geological Survey, Special Volume 2, 270p. Accompanied by Preliminary Map P.2715, scale 1:600 000.

Cowell, D.W. and Associates, Inc. 1989. Surface water quality, Bruce Peninsula and Fathom Five National Parks: April-May, 1989; Environment Canada, Inland Waters Directorate, Water Quality Branch, Burlington, Ontario, 39p.

Cowell, D.W., Fisher, J., Delorme, R., Stewart, C., Buck, M., Ferwerda, P., Janes, T. and Czok, R. 1994. Geomorphological inventory of Bruce Peninsula National Park and Fathom Five National Marine Park, Vol. I. Surface geomorphological inventory: St. Edmunds Township, Cabot Head and islands between Tobermory and Manitoulin; Vol. II. Underwater geomorphological inventory: Fathom Five National Marine Park; Reports and maps prepared for Canadian Parks Service, Ontario Region by Geomatics International Incorporated, v.I, 120p., v.II, 87p.

Cowell, D.W. and Ford, D.C. 1975. The Wodehouse Creek karst, Grey County, Ontario; Canadian Geographer, v.19, no.3, p.196-205.

——— 1980. Hydrochemistry of the dolomite karst: the Bruce Peninsula of Ontario; Canadian Journal of Earth Sciences, v.17, p.520-526.

——— 1983. Karst hydrogeology of the Niagara Escarpment, Bruce Peninsula, Ontario; V.T. Stringfield Symposium on Karst Hydrology; Journal of Hydrology, v.16, p.163-168.

Cowell, D.W. and Woerns, N. 1977. Earth Science candidate Nature Reserves in the Niagara Escarpment Planning Area; Ontario Ministry of Natural Resources, Park Planning Branch, Miscellaneous Report, 165p.

Ford, D.C. 1961. The Bonnechere caves, Renfrew County, Ontario: a note; Canadian Geographer, v.3, p.22-25.

——— 1983. Effects of glaciation upon karst aquifers in Canada; Journal of Hydrology, v.61, p.149-158.

Ford, D.C. and Quinlan, J.F. 1973. Theme and resource inventory study of the karst regions of Canada; National and Historical Parks Branch, Canadian Department of Energy, Mines and Resources, Project A, contract 73-32, p.9-21.

Ford, D.C. and Williams, P.W. 1989. Karst geomorphology and hydrology; Unwyn Hyman, London, United Kingdom, 601p.

Goodchild, M.F. 1978. Final Report – Cave safety study, Flowerpot Island, Georgian Bay Islands National Park; Report prepared for Parks Canada, Cornwall, Ontario, 92p.

——— 1984. Final Report – Resource management study of caves, Tobermory Islands Unit, Georgian Bay Islands National Park; Report prepared for Parks Canada, Cornwall, Ontario, 130p.

Gordon, M. 2005. Rock watching: adventures above & below Ontario; The Boston Mills Press, Erin, Ontario, 192p.

Karrow, P.F. 1973. Bedrock topography in southwestern Ontario: a progress report; Geological Association of Canada, Proceedings, v.25, p.67-77.

Kor, P.S.G. and Cowell, D.W. 1998. Evidence for catastrophic subglacial meltwater sheetflood events on the Bruce Peninsula, Ontario; Canadian Journal of Earth Sciences, v.35, p.1180-1202.

Kor, P.S.G., Shaw, J. and Sharpe, D.R. 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view; Canadian Journal of Earth Sciences, v.28, p.623-642.

Kunert, M. and Coniglio, M. 2002. Origin of vertical shafts in bedrock along the Eramosa River valley near Guelph, southern Ontario; Canadian Journal of Earth Sciences, v.39, p.43-52.

Ongley, E.D. 1965. A study of caves in southern Ontario; unpublished BA thesis, University of Toronto, Toronto, Ontario, 117p.

Palmer, A.N. 1991. Origin and morphology of limestone caves; Geological Society of America Bulletin, v.103, p.1-21.

Pluhar, A. and Ford, D.C. 1970. Dolomitic karren of the Niagara escarpment, Ontario, Canada; Zeitschrift für Geomorphologie, v.14, p.411-428.

Russell, D.F. 2004. Nutrient Management Project: characterization of fractured Paleozoic bedrock in thin drft areas of southern Ontario; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.34-1 to 34-7.

Sanford, B.V. 1993. St. Lawrence Platform: economic geology; *in* Sedimentary cover of the craton in Canada; Geological Survey of Canada, Geology of Canada, No. 5, p.787-798.

Shaw, J. 1996. A meltwater model for Laurentide subglacial landscapes; *in* Geomorphology sans frontières, John Wiley & Sons Ltd., p.181-236.

Shaw, J. and Gilbert, R. 1990. Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State; Geology, v.18, p.1169-1172.

Spencer, J.W. 1890. Origin of the basins of the Great Lakes of America; American Geologist, v.7, p.86-97.

Straw, A. 1968: Late Pleistocene glacial erosion along the Niagara Escarpment of southern Ontario; Geological Society of America Bulletin, v.79, p.889-910.

Strynatka, S.A. 2003. Nutrient management project: Characterization of thin drift cover over various Paleozoic bedrock formations in southern Ontario; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.26-1 to 26-5.

Tinkler, K.J. and Stenson, R.E. 1992. Sculpted bedrock forms along the Niagara Escarpment, Niagara Peninsula, Ontario; Géographie physique et Quaternaire, v.46, p.195-207.

White, W.B. 1988. Geomorphology and hydrology of karst terrains; Oxford University Press, New York, 464p.

Worthington, S.R.H. 2001. Depth of conduit flow in unconfined carbonate aquifers; Geology, v.29, p.335–338.

——— 2002. Test methods for characterizing contaminant transport in a glaciated carbonate aquifer; Environmental Geology, v.42, p.546-551.

——— 2003. A comprehensive strategy for understanding flow in carbonate aquifers; *in* Karst modeling, The Karst Waters Institute, Charles Town, West Virginia, Special Publication 5, p.30-37.

Worthington, S.R.H., Davies, G.J. and Ford, D.C. 2000. Matrix, fracture and channel components of storage and flow in a Paleozoic limestone aquifer; *in* Groundwater flow and contaminant transport in carbonate aquifers, Balkema, Rotterdam, p.113-128.

Worthington S.R.H., Ford, D.C. and Beddows, P.A. 2000. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution; *in* Speleogenesis: evolution of karst aquifers, National Speleological Society, Huntsville, Alabama, p.463-472.

28. Project Unit 05-013. Bedrock Topography and Drift-Thickness Maps, Southern Ontario

J. Shirota[1], F.R. Brunton[1] and R.I. Kelly[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The purpose of this project is to provide comprehensive, updated, digital bedrock topography and drift thickness maps of southern Ontario. Advances in data storage and retrieval of the extensive oil and gas well records, and water-well records, especially those data acquired over the last 40 years, have made updated maps both timely and possible. Previous attempts did not have access to such comprehensive databases (e.g., Karrow 1973; Chapman and Putnam 1984). The project forms part of the geoscience data sets being generated by the Ontario Geological Survey for input to source water protection plans.

This paper reports on initial work completed for southwestern Ontario. The techniques employed by this project will be used for the final map that will cover all of southern Ontario—emphasizing those areas covered by rocks of Paleozoic age. The bedrock in southwestern Ontario is predominantly Paleozoic in age and sedimentary in origin. Differential weathering of the interbedded limestones, dolostones, shales, sandstones and evaporites over thousands of years has resulted in the current cuesta-like topography. Glaciations over the past few million years have greatly influenced the current bedrock surface and resulted in the burial of much the bedrock surface by variable thicknesses of till, clay, sand and gravel deposits. This project has enabled better delineation of the buried erosional cuesta topography and the regional extent of significant buried valleys throughout southwestern Ontario.

The approximate thickness of the Quaternary sediments was determined by subtracting the bedrock surface from the provincial digital elevation model (DEM). Drift-thickness maps are also used to delineate areas of thin surficial sediment cover where bedrock aggregate resources can be obtained at lower cost. Furthermore, the bedrock topography and drift-thickness maps may be used in conjunction with other data sets to develop such products as groundwater resource maps and susceptibility maps related to karstification and groundwater contamination.

DATA SOURCES AND PROCESS

The input data sets were standardized and merged into consistent database tables. This involved standardization of terminology, unit conversion, and removal of unreliable records.

Water Wells

All material descriptions in water-well records were translated into either "rock" or "overburden" using a translation table. For each well, the depth to bedrock was determined. Using the DEM, the

---

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.28-1 to 28-6

© Queen's Printer for Ontario, 2005

Table 28.1. Breakdown of the input data sources.

Source	Count
Water Wells (Reaching Bedrock)	158 085
Bedrock Polygon Converted to Points	*145 613*
Outcrops from Paleozoic Maps	30 209
Water Wells (Not Reaching Bedrock)	22183
Engineering Boreholes	16 101
Oil and Gas Wells	13 715
Outcrops from Surficial Geology of Southern Ontario	7247
	393 153

elevation of the bedrock surface was calculated for each location in the database. Those wells that did not reach bedrock were separated and stored in a separate table.

Engineering Boreholes

The Urban Geology Automated Information System (UGAIS) database housed by the OGS includes a field indicating the depth to bedrock. This field and the DEM were used to calculate the elevation of the bedrock surface at each location.

Oil and Gas Wells

The oil and gas wells database maintained by the Ontario Oil, Gas and Salt Resources Library contained information on bedrock formations and their relative depths. The bedrock surface was generally the top of the youngest bedrock unit. However, in some cases, the record skipped some of the upper bedrock units making it difficult to define the true bedrock surface elevation. Whether a record skipped younger bedrock units or not seemed to depend on which unit the drillers were targeting (for oil and gas exploration), but no systematic way of filtering this was found. All records were used with the top elevations of the youngest bedrock units assuming that any erroneous records could be identified after the first attempt of interpolation.

Outcrops

All outcrop locations were retrieved from the surficial geology of southern Ontario map (OGS 2003) and the existing Paleozoic bedrock maps, and the depth to bedrock of 0 m was assigned to these points. In addition to these point data, polygonal areas of exposed bedrock and thin drift were added by converting each polygon to points at a regularly spaced interval. A depth of 1 m was assigned to these points.

The above data sets were used to create the first interpolation of the bedrock surface. The water wells that did not reach bedrock, but went deeper than the result of the first interpolation, were queried out and added back into the input data set. This was done because the bottom depths of these records indicated that the bedrock was "at least this deep" and could be used to effectively "push down" the surface.

The records with unreliable location information and "previously dug" holes were removed. At the end of the cleaning process, the merged database contained 393 153 records (Table 28.1). Additional data were recently acquired including drill-hole records from the GSC and the OGS. These records will be added to the current working database.

The study area was divided into several portions ("tiles") in order to facilitate the computing process and manual inspection. Records in each tile were carefully inspected and surfaces were interpolated in small sections using ordinary kriging in ESRI® ArcGIS® software. The search radius type and the number of points were set to "variable" and 12, respectively. The resulting surfaces were carefully inspected and any conspicuous patterns ("bull's-eye") were identified. When a "bull's-eye" occurred, the points that were causing the bull's-eye were manually inspected and compared with their neighbouring points. All erroneous records and any anomalies that were insignificant at this scale of mapping were removed. Once these records were removed, the surface was re-interpolated. This process was repeated until each tile was free of major bull's-eyes.

PRELIMINARY RESULTS

Those tiles covering much of southwestern Ontario have been completed. The resulting bedrock surface shows potential bedrock valleys and cuesta-like topography (Figure 28.1). Some of these features are buried by glacial sediments and are not apparent on the DEM surface. A number of bedrock valleys and topographic features are shown on Figure 28.2 and discussed in more detail below.

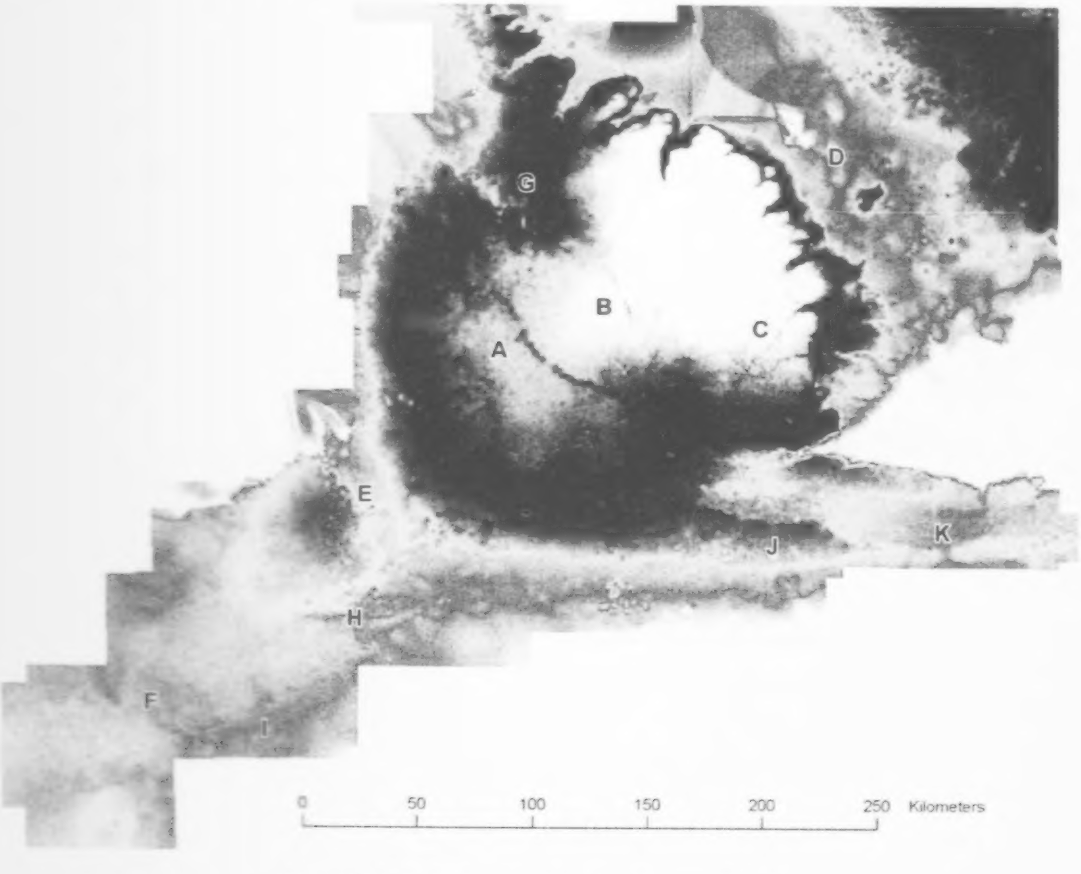


Figure 28.1. Bedrock topography of southwestern Ontario.

A. Wingham Valley

This buried valley is known as the Wingham valley (Karrow 1973). The southeast-trending valley can be clearly traced on the bedrock surface from Wingham to approximately 10 km west of Waterloo, where it merges with the Dundas Valley. An associated buried-valley-like feature extends southward from and connects up with the Wingham valley at Wingham. This feature can be traced for more than 10 km. The associated valley seems to continue to the north and drain into Lake Huron, but its exact path is unclear.

B. Walkerton Valley (Southern Extension)

This is the southern extension of the Walkerton valley (Karrow 1973). This valley stretches from Drayton to approximately 3 km west of Mount Forest where it drains into the large re-entrant-like topographic low (G). However, it is questionable if this valley extends all the way to Walkerton and continues along the present-day Saugeen River drainage into Lake Huron, as is shown in Karrow's map.

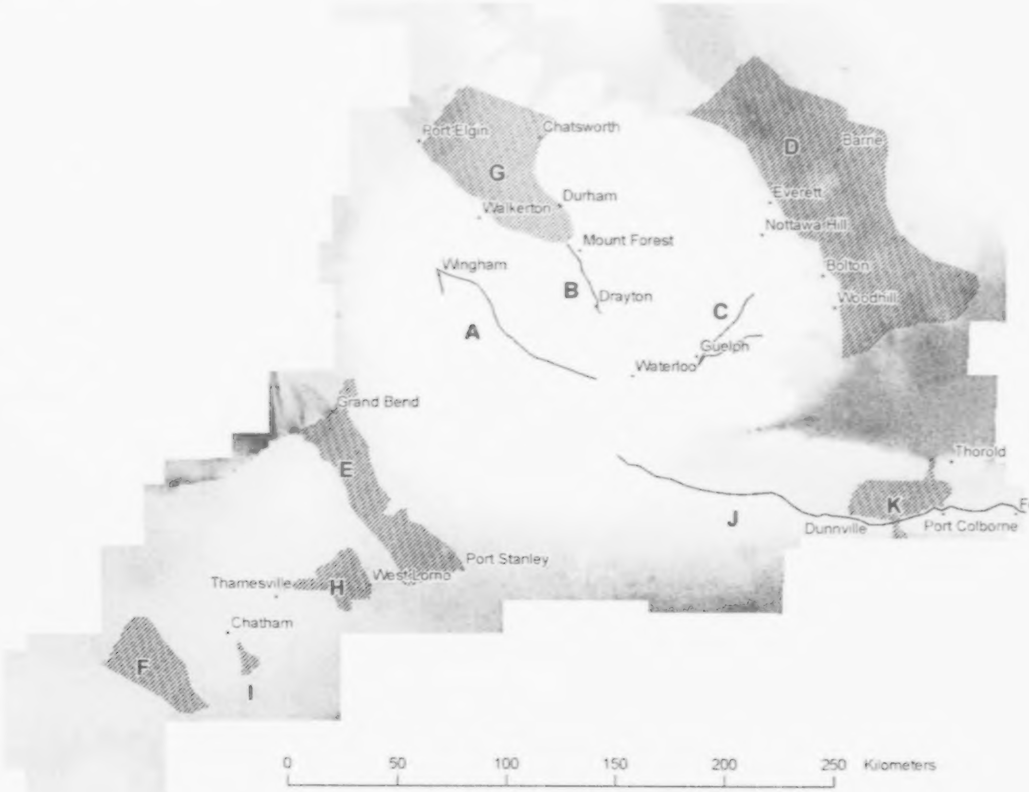

Port Elgin
Chatsworth
G
Walkerton
Durham
Mount Forest
Wingham
B
Drayton
A
C
Guelph
Waterloo
D
Barrie
Everett
Nottawa Hill
Bolton
Woodhill
Grand Bend
E
Thorold
K
Fort Erie
J
Dunnville
Port Colborne
Port Stanley
West Lorne
Thamesville
H
Chatham
F
I
0
50
100
150
200
250
Kilometers

Figure 28.2. Location of some major bedrock valleys and topographic features (identified by line or hachured area) and labelled by letter (*see* text for description).

C. Older Drainage Network

Several bedrock valleys are present near Guelph (Karrow 1973). The geometry of this older drainage network corresponds to the present one, which includes Eramosa River and Blue Springs Creek, but is less meandering.

D. Laurentian Valley

The Laurentian Valley is clearly defined by the resulting bedrock surface mapping. A positive topographic feature is apparent approximately 15 km south of Barrie, but there are not enough drill holes reaching bedrock to confirm this. Smaller re-entrant-like valleys exist along the western edge of the Laurentian Valley. Some of these valleys such as the ones near Woodhill, Bolton, Nottawa Hill and Everett are partly buried by the overburden.

E. Valley and Ipperwash Escarpment

A topographic low area stretching between Grand Bend and Port Stanley is clearly defined by the mapping. At the northwest end of this valley, an escarpment can be found, which is referred to as the Ipperwash Escarpment (Karrow 1973). The escarpment shows vertical drops of more than 50 m in some areas.

F. Chatham Sag

The process clearly delineated the structural low between Lake St. Clair and Lake Erie known as Chatham Sag (Karrow 1973).

G. Large Re-entrant Valley

The entire area surrounded by Chatsworth, Durham, Mount Forest, Walkerton and Port Elgin seems to be a large re-entrant valley.

H. Re-entrant Valley

This bedrock valley stretches from Thamesville eastward towards West Lorne. Although the main axis seems to be in the east-west orientation, the valley becomes significantly wider to the east of Thamesville giving it a re-entrant-like geometry. Several smaller valley-like features also exist in this area. These will be investigated further.

I. Re-entrant Valley

This valley emerges approximately 5 km southeast of Chatham and continues for approximately 14 km to the southeast until it disappears near Lake Erie. The valley becomes wider as it approaches Lake Erie giving it a re-entrant-like geometry.

J. Onondaga Escarpment

The Onondaga Escarpment is partly buried by the Quaternary sediments between Fort Erie and Dunnville. The interpolated bedrock surface shows the Erigan Valley (K), which cuts through this escarpment, as well as a few additional "notches" along the escarpment near the Lake Erie shoreline.

K. Erigan Valley

The Erigan Valley cuts the Onondaga Escarpment (J) approximately 15 km west of Port Colborne, extends in the northeast direction, and intersects the Niagara Escarpment approximately 6 km west of Thorold. However, the exact path of this valley is unclear.

FUTURE WORK

The next phase of this project will be to complete the bedrock topography map for south-central and southeastern Ontario. Further efforts will also concentrate on determining the nature of overburden material within the various bedrock valleys and re-entrants throughout southwestern Ontario. A final GIS-based bedrock topography map for all of southern Ontario is expected to be released in the latter part of 2006.

REFERENCES

Karrow, P.F. 1973. Bedrock topography in southwestern Ontario: a progress report; Geological Association of Canada, Proceedings, v.25, p.67-77.

Chapman, L.J. and Putnam, D.F. 1984. The physiography of southern Ontario, 3rd ed.; Ontario Geological Survey, Special Volume 2, 270p. Accompanied by Preliminary Map P.2715, scale 1:600 000.

Ontario Geological Survey 2003. Surficial geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 128, 2 CD-ROMs.

29. Project Unit 05-011. Paleozoic Geology Map of Southern Ontario

J.E.P. Dodge[1], D.K. Armstrong[1] and R.I. Kelly[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The province of Ontario is currently developing legislation that will see the implementation of Source Water Protection Plans across much of the province. A Technical Experts Committee (TEC) struck by the province in late 2003 identified a number of critical data sets , including geologic ones, required for source protection planning. One of the geologic data sets identified was a geographic information system (GIS)-based Paleozoic bedrock geology map for southern Ontario. This large-scale map would provide information that could be used for groundwater mapping and modelling, water quality and watershed characterization as well as vulnerability and susceptibility mapping.

Over the past 31 years, the Ontario Geological Survey (OGS) has completed Paleozoic mapping, primarily at a scale of 1:50 000, for most of southern Ontario. This mapping provides a wealth of information on the stratigraphy, paleontology and potential mineral resources of the Paleozoic bedrock. Over the years, users of these maps have been many and the uses varied. However, with increased usage of digital mapping software, and demand from clients for readily accessible, user-friendly, geological maps, the existing maps have many limitations for use in the digital world. Generation of a seamless, attributed GIS-based Paleozoic map, for not only source water protection applications, but more traditional uses as well, will provide users with a flexible, easily used and understood product.

DATA SOURCES AND PROCESS

The compilation area covers 107 complete and partial 1:50 000 scale National Topographic System (NTS) map sheets in southern Ontario (Figure 29.1). A total of 56 published 1:50 000 scale maps covering 82 NTS map sheets are available for the area. Two areas (hatched areas on Figure 29.1) covering approximately 41 NTS sheets do not have detailed map coverage due to the thick cover of glacial drift that exists in these regions. Currently, the only available digital map for these areas is the *Geology of Ontario* at a scale of 1:1 000 000 (OGS 1991).

To complete the project, procedures and protocols developed by the OGS during completion of a seamless surficial geology map for southern Ontario (Bajc et al. 2001; Gao, Dodge and MacDonald 2002) will be drawn upon. The first phase of this project, as set out in the work plan, is to compile all existing 1:50 000 scale Paleozoic maps into a standardized, GIS structured format. The software used to create the seamless Paleozoic coverage will be ESRI® ArcMap® 8.3 and ArcInfo® Workstation. The original, maps (tiles) exist as either digital vector or raster format. All vector maps will be converted to ESRI's coverage format. Maps that require vectorization will be digitized (heads up) using georeferenced files in tagged image file format (*.tif*).

Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, p 29-1 to 29-3.

© *Queen's Printer for Ontario, 2005*

ATTRIBUTES AND METHODOLOGY

Polygonal, point and line information will be captured during the automation process. Attribute tables will contain various geological related information on Paleozoic geological units, quarries and outcrops, geologic contacts and faults as well as key section descriptions. Phase I tasks for the project include the following

- Capture all existing point, line and polygonal information from existing Paleozoic maps published by the Ontario Geological Survey;
- Clip all coverages to a new neatline to ensure smooth migration of maps to single appended Ontario coverage;
- Standardize attribute tables;
- Create a geological symbols library for ArcMap® 8.x;
- Develop a provincial legend that will translate all original map legends;
- Generate an appended coverage for southern Ontario.

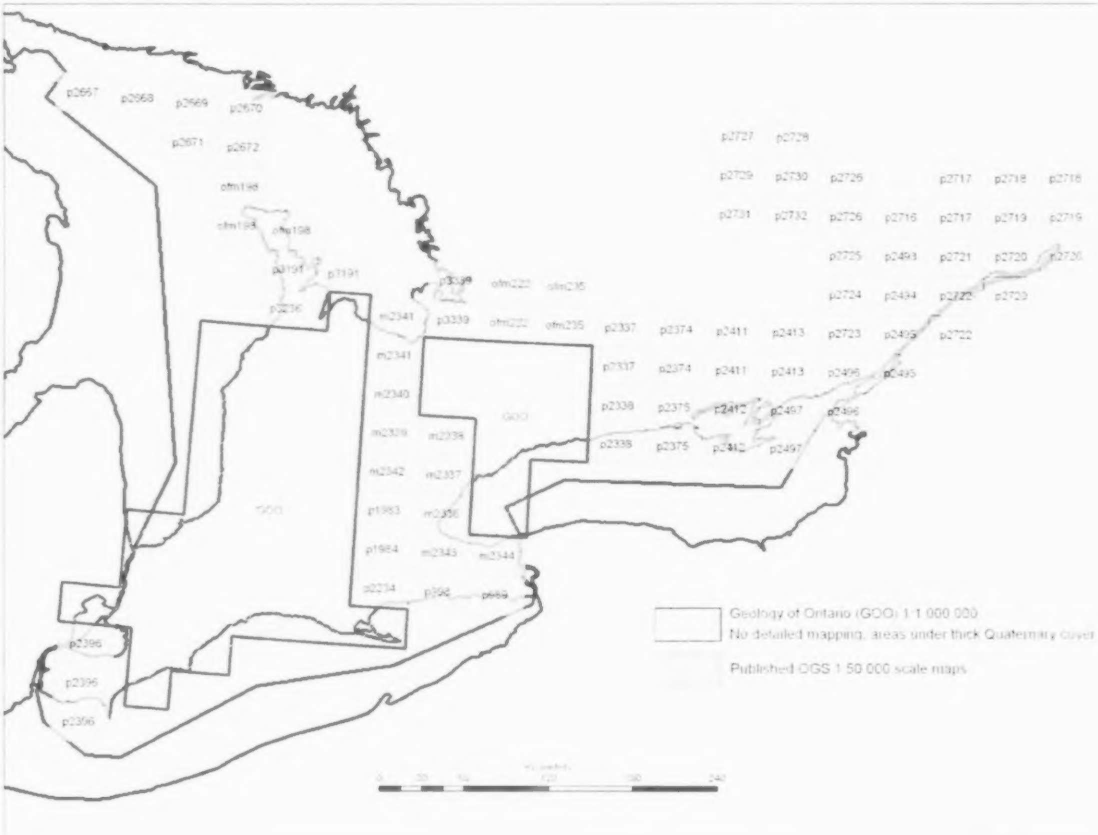

GOO
GOO
Geology of Ontario (GOO) 1:1 000 000
No detailed mapping, areas under thick Quaternary cover
Published OGS 1:50 000 scale maps
0
30
60
120
180
240

Figure 29.1. Distribution of Paleozoic maps for southern Ontario.

ATTRIBUTES AND METHODOLOGY

Polygonal, point and line information will be captured during the automation process. Attribute tables will contain various geological related information on Paleozoic geological units, quarries and outcrops, geologic contacts and faults as well as key section descriptions. Phase I tasks for the project include the following

- Capture all existing point, line and polygonal information from existing Paleozoic maps published by the Ontario Geological Survey;
- Clip all coverages to a new neatline to ensure smooth migration of maps to single appended Ontario coverage;
- Standardize attribute tables;
- Create a geological symbols library for ArcMap® 8.x;
- Develop a provincial legend that will translate all original map legends;
- Generate an appended coverage for southern Ontario.

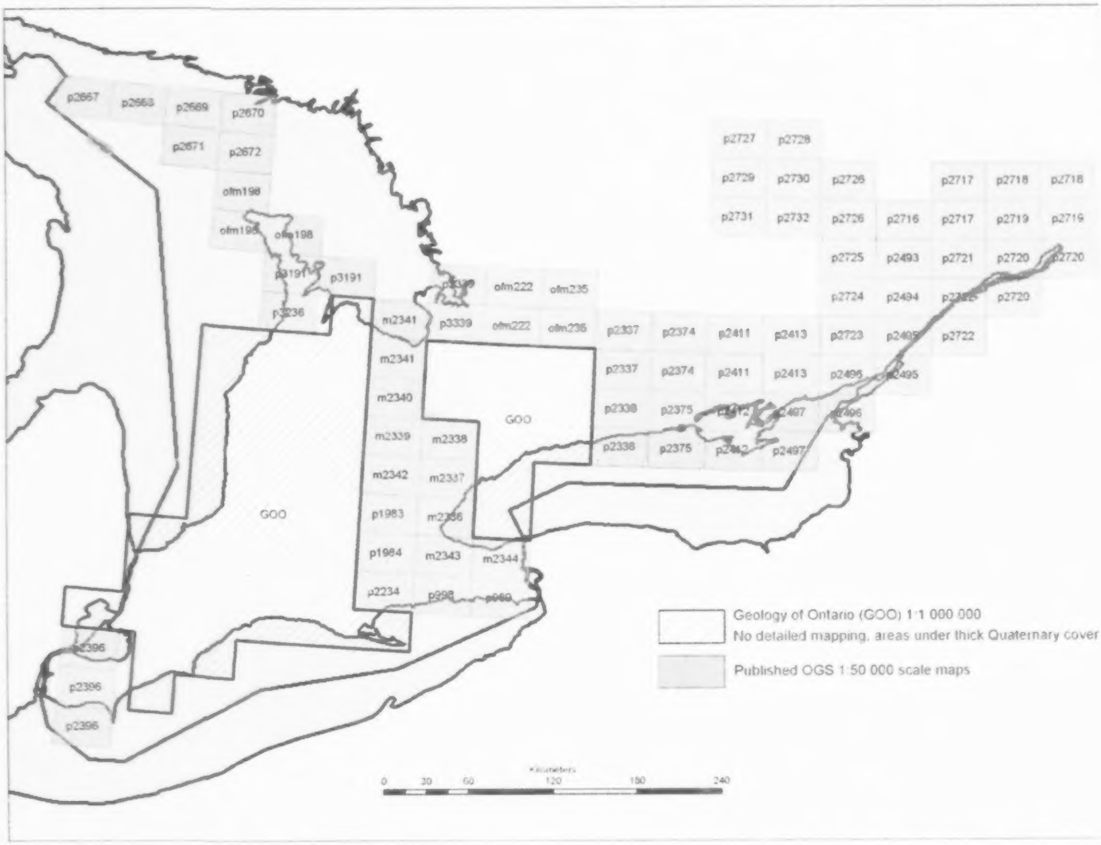

p2667
p2668
p2669
p2670
p2671
p2672
ofm198
ofm198
p3191
p3191
p3236
ofm222
ofm235
m2341
p3339
ofm222
ofm235
m2341
m2340
m2339
m2338
m2342
m2337
p1983
m2336
p1984
m2343
m2344
p2234
p998
p2396
p2396
p2396
GOO
GOO
p2727
p2728
p2729
p2730
p2726
p2717
p2718
p2718
p2731
p2732
p2726
p2716
p2717
p2719
p2719
p2725
p2493
p2721
p2720
p2720
p2724
p2494
p2720
p2337
p2374
p2411
p2413
p2723
p2722
p2337
p2374
p2411
p2413
p2496
p2495
p2338
p2375
p2497
p2338
p2375
p2497
Geology of Ontario (GOO) 1:1 000 000
No detailed mapping, areas under thick Quaternary cover
Published OGS 1:50 000 scale maps
Kilometers
0
30
60
120
180
240

Figure 29.1. Distribution of Paleozoic maps for southern Ontario.

The second phase of this project will be the generation of a "seamless map". Appending 56 maps, each with different authors and different legends, will be a challenging task. During this phase of the project, all boundary faults that exist between individual map sheets will be corrected. Corrections will be based on field investigations carried out by OGS geologists, review of bedrock geological maps, Aggregate Resource Inventory Papers (ARIPs), as well as a digital elevation model (DEM). The 2 areas where detailed mapping does not exist will require the use of other data sources for corrections. These areas (*see* Figure 29.1) are difficult to map because they are covered by thick Quaternary sediments. For these areas, the OGS will rely on information that can be garnered from cores and borehole logs generated by previous OGS drilling, water well records, digital subsurface bedrock data obtained from the Ontario Oil, Gas and Salt Resources Library Service as well as an updated bedrock topographic surface for southern Ontario (*see* Shirota, F.R. Brunton and R.I. Kelly, this volume). Other data sources may include existing bedrock maps published by the Geological Survey of Canada. The resultant product of phase II will be an easily understood user friendly tiled seamless Paleozoic bedrock map of southern Ontario.

TIMETABLE

To date, preliminary data capture and integration of existing map data into standardized ArcInfo® coverages and associated attribute tables is underway. This work is expected to be completed by the spring of 2006. Some preliminary field checking was completed during the summer of 2005 with the bulk of field checking and map unit correction work expected to be completed by mid-2006. A final seamless map is expected to be completed by the fall of 2006.

REFERENCES

Bajc, A., Leney, S., Evers, S., van Haaften, S. and Ernsting, J. 2001. A seamless Quaternary geology map of southern Ontario; *in* Summary of Field Work and Other Activities 2001, Ontario Geological Survey, Open File Report 6070, p.33-1 to 33-5.

Gao, C., Dodge, J.E.P. and MacDonald, I.M.L. 2002. A seamless Quaternary geology map of southern Ontario : Second Phase; *in* Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.29-1 to 29-2.

Ontario Geological Survey 1991. Bedrock geology of Ontario, southern sheet; Ontario Geological Survey, Map 2544, scale 1:1 000 000.

30. Project Unit 04-028. An Investigation of Buried-Valley Aquifer Systems in the Area North of Lake Ontario

S.D. Davies[1] **and S. Holysh**[1]

[1]Conservation Authorities Moraine Coalition

INTRODUCTION

An investigation has been undertaken into buried-valley aquifer systems in southern Ontario. The Conservation Authorities Moraine Coalition (CAMC) was formed in 2001 to study the groundwater resources of the 9 conservation authorities that drain off of the Oak Ridges Moraine (Figure 30.1). In 2004, the Ontario Geological Survey (OGS) partnered with CAMC to undertake a study to investigate buried-valley aquifer systems in the study area. The OGS, CAMC and Geological Survey of Canada (GSC) have a common interest in evaluating the significance of buried valleys as an important aquifer type and are working in partnership regarding the investigation of buried-valley aquifers in this part of southern Ontario.

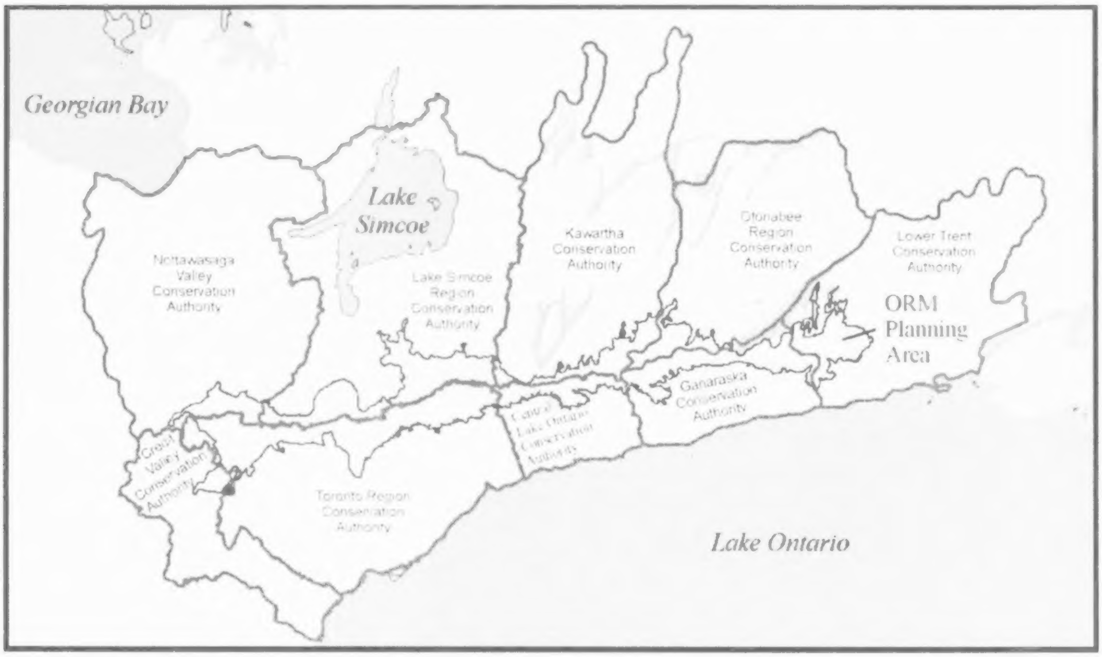

Georgian Bay
Lake Simcoe
Nottawasaga Valley Conservation Authority
Lake Simcoe Region Conservation Authority
Kawartha Conservation Authority
Otonabee Region Conservation Authority
Lower Trent Conservation Authority
ORM Planning Area
Ganaraska Conservation Authority
Central Lake Ontario Conservation Authority
Credit Valley Conservation Authority
Toronto Region Conservation Authority
Lake Ontario

Figure 30.1. Location of study area showing the boundaries of the 9 conservation authorities that are part of the Conservation Authorities Moraine Coalition (CAMC).

Summary of Field Work and Other Activities 2005
Ontario Geological Survey, Open File Report 6172, p.30-1 to 30-7.

© *Queen's Printer for Ontario, 2005*

30. Project Unit 04-028. An Investigation of Buried-Valley Aquifer Systems in the Area North of Lake Ontario

S.D. Davies[1] **and S. Holysh**[1]

[1]Conservation Authorities Moraine Coalition

INTRODUCTION

An investigation has been undertaken into buried-valley aquifer systems in southern Ontario. The Conservation Authorities Moraine Coalition (CAMC) was formed in 2001 to study the groundwater resources of the 9 conservation authorities that drain off of the Oak Ridges Moraine (Figure 30.1). In 2004, the Ontario Geological Survey (OGS) partnered with CAMC to undertake a study to investigate buried-valley aquifer systems in the study area. The OGS, CAMC and Geological Survey of Canada (GSC) have a common interest in evaluating the significance of buried valleys as an important aquifer type and are working in partnership regarding the investigation of buried-valley aquifers in this part of southern Ontario.

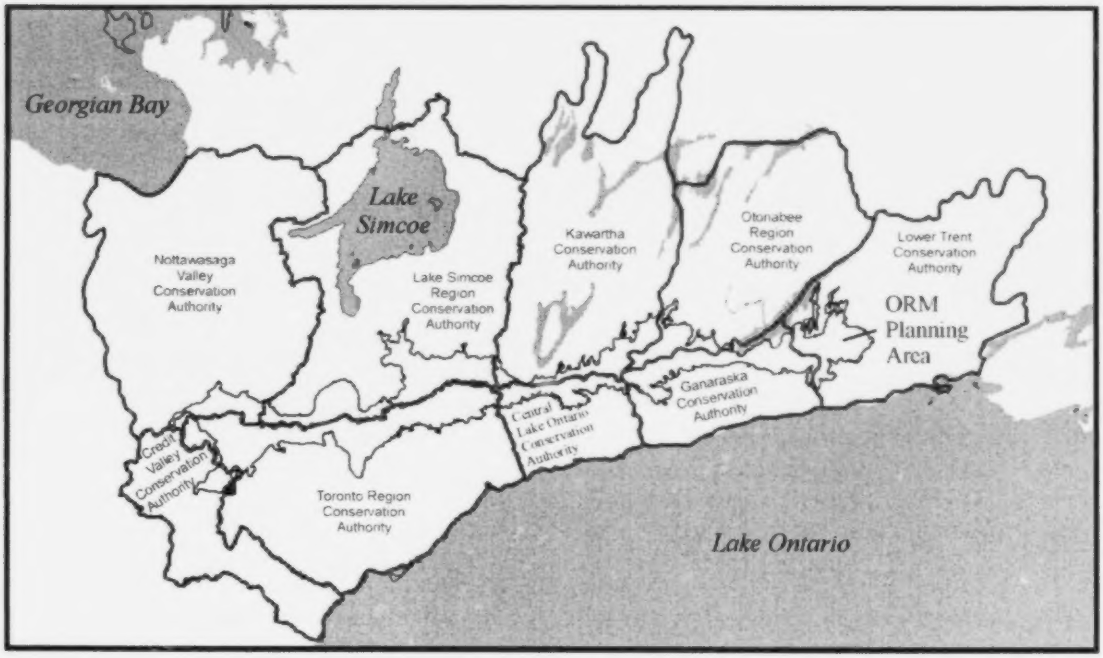

Georgian Bay
Lake Simcoe
Nottawasaga Valley Conservation Authority
Lake Simcoe Region Conservation Authority
Kawartha Conservation Authority
Otonabee Region Conservation Authority
Lower Trent Conservation Authority
ORM Planning Area
Ganaraska Conservation Authority
Central Lake Ontario Conservation Authority
Credit Valley Conservation Authority
Toronto Region Conservation Authority
Lake Ontario

Figure 30.1. Location of study area showing the boundaries of the 9 conservation authorities that are part of the Conservation Authorities Moraine Coalition (CAMC).

Summary of Field Work and Other Activities 2005.
Ontario Geological Survey, Open File Report 6172, p.30-1 to 30-7.

© Queen's Printer for Ontario, 2005

Despite being hydrogeologically significant in the Great Lakes area, and in particular in Ontario, buried-valley aquifers remain poorly understood from both a sedimentological and a hydrogeological perspective (Sharpe and Russell 2004). Because of their narrow widths, they are difficult to delineate and characterize (e.g., Sharpe et al. 2004); hence, there is a need for the acquisition of high-quality data. Few critical data have been gathered to test models with respect to valley origin. A variety of mechanisms and hypotheses for the formation and filling of bedrock valleys have been reported (Scheidegger 1980) that range from preglacial fluvial (Spencer 1890) to glacial (Straw 1968) or subglacial fluvial systems (i.e., tunnel channels) (Kor and Cowell 1998).

Much of this study is focussed on areas influenced by the Laurentian Channel. This channel has been interpreted as a broad preglacial bedrock depression that extends from Georgian Bay to Lake Ontario. The Laurentian Channel was first identified in the late 1800s (Spencer 1890). It is nearly 100 km long, in places over 25 km wide, and is believed to have acted to drain the mid-continent region prior to the formation of the Great Lakes. Given the depth, length and width of the feature, it is likely to have a considerable influence on groundwater movement over a large part of southern Ontario. The sedimentary infill of this buried-valley feature may have been modified by glacial or subglacial fluvial systems (tunnel channels). These hypotheses were tested as part of the current study. Both within and outside of buried bedrock valleys, subglacial fluvial systems are thought to be responsible for the origin of a number of high yield aquifers (Sharpe et al. 1996). Depending on channel infill materials, these channels can strongly affect the amount of vertical leakage between groundwater flow in near-surface aquifers and groundwater in any deeper aquifers.

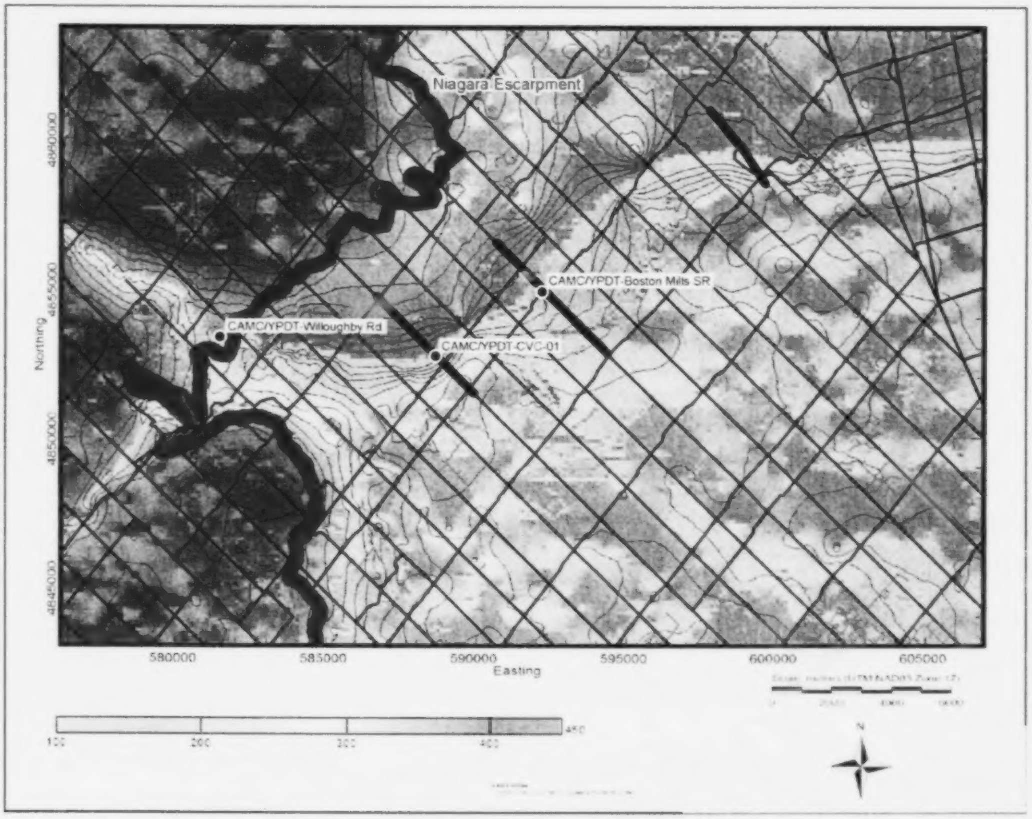


Figure 30.2. Caledon East bedrock valley, showing the locations of seismic lines and boreholes.

This paper describes the work completed in the Caledon East area within Peel Region; and on a tunnel channel system southwest of Port Perry. Prior to 2005, seismic geophysical surveys were undertaken at each location and cored boreholes were also drilled at the Caledon location. In addition to detailed geological logging of the boreholes, a suite of downhole geophysical tools were also run on the boreholes to better quantify the response of the subsurface geology and to help in describing the subsurface glacial stratigraphy. The work at Port Perry was driven, in part, by the need for Durham Region to secure additional sources of potable water in that area.

FIELD PROGRAM

Caledon East Buried Valley

In 2005, 2 mud rotary boreholes were completed to bedrock in the Caledon East buried valley (Figure 30.2). A 177.7 m deep borehole (CAMC/YPDT-Boston Mills SR) was completed through the valley infill sediments on Boston Mills Sideroad, just west of the Mountainview Road seismic line that was completed in 2004 (Davies and Holysh 2004). This borehole was converted to a 76 mm monitoring well. Downhole geophysics and a single well pumping test are scheduled for this well in the fall of 2005.

A 178.31 m deep borehole (CAMC/YPDT-Willoughby Rd.) was completed on the brow of the Niagara Escarpment along the thalweg of the interpolated bedrock valley. This work was undertaken in collaboration with a private citizen, and a 153 mm stainless steel domestic water well was installed in the basal granular aquifer encountered.

Port Perry Tunnel Channel

In the Port Perry area, a 125.3 m deep dual air rotary borehole was completed to bedrock along seismic line 2 (Figure 30.3), one of the 2 seismic lines previously completed in 2004 (Holysh, Davies and Goodyear 2004). The borehole was located in an area identified as a channel feature based on the seismic data and approximately along the thalweg of a topographical feature interpreted as a tunnel channel (Russell, Arnott and Sharpe 2003). The drilling encountered a significant aquifer with potential as a municipal supply aquifer. As a result, the drilling program was expanded by the Region of Durham to include the drilling of a production well and 2 additional observation wells. A pumping test and downhole geophysical logging are to be completed by the Region of Durham in the fall of 2005.

Other Work

At the time of writing, a high-quality PQ continuously cored borehole was being drilled along one of the seismic lines completed in the Barrie area in 2004 (Davies and Holysh 2004). Also, a downhole geophysical logging program was underway for up to 12 recently drilled boreholes. The results of these activities were not available at the time of writing.

PRELIMINARY RESULTS

Caledon East Buried Valley

The seismic survey completed in the Caledon East area in 2004 indicated the presence of a deep bedrock valley approximately 70 m deeper than the surrounding bedrock topography and up to 1.5 km wide. A thick sand and gravel aquifer that may be continuous along the base of the bedrock valley system was encountered through drilling of deep borehole CAMC/YPDT-CVC-01 in 2004 (*see* Figure 30.2). The mud rotary boreholes drilled in 2005 were intended to better define the bedrock surface and provide preliminary stratigraphic information. Borehole CAMC/YPDT-Boston Mills SR was also intended to confirm seismic stratigraphic interpretations.

Preliminary results corroborate the depth to bedrock and the interpretation of the seismic facies from the Mountainview Road line. In the CAMC/YPDT-Boston Mills SR borehole, the bedrock surface was encountered at 179 m depth. The stratigraphy was predominantly fine-grained sediments (silt, clay and fine sand) to a depth of about 153 m. Below this depth, approximately 25 m of sand and gravel with significant aquifer potential was encountered. Downhole geophysics to be completed in the screened monitoring well will help to further describe the stratigraphy. Water levels and a pumping test to be completed in this well will further enhance the hydrogeological analysis of this bedrock valley system.

The mud rotary borehole completed on the brow of the Niagara Escarpment (CAMC/YPDT-Willoughby Rd.) confirmed the western upgradient extension of the buried bedrock valley. The bedrock surface was encountered at a depth of 175 m and a 20 m thick sand and gravel aquifer was located above the bedrock surface at this location. This aquifer is scheduled to be pump-tested, but preliminary indications are that it is very transmissive and may be capable of sustaining a pumping rate of several hundred gallons per minute.

The work completed in 2004 and 2005 provided critical information in delineating this valley and, to some extent, the nature of its sedimentary infill. The location of this valley feature suggests that it is related to the Laurentian Channel, likely serving as a significant tributary at the time when the Laurentian River was active. The depositional record for the Caledon East valley infill sediments suggests that these sediments might be much younger than the valley itself.

Glaciofluvial tunnel channel processes likely affected much of the sampled portions of the valley. Assuming continuity between the 3 seismic profiles and the 3 boreholes, a 20 to 100 m thick gravel-and-sand aquifer extending at least 10 to 12 km in length and 1 to 2 km wide exists in the deeper portions of the valley. This coarse sediment is flanked and overlain by sands and silts about 100 m thick that may be expected to extend the entire width (2 to 4 km) of the bedrock valley and along much of its length. A continuous blanket of fine-grained clay-silt rhythmite sediments, at least 20 to 30 m thick, caps the channel-fill sequence.

At the eastern end of this buried valley in the vicinity of Bolton, the infill sediments trend to the northeast and are expected to have some continuity with the Holland Marsh tunnel channel system (Russell, Arnott and Sharpe 2003). In the re-entrant valley at the Niagara Escarpment, high-energy erosion probably removed most of the earlier sediments. In the vicinity of Bolton, it could be expected that the older coarse- to fine-grained strata has been preserved, dissected by more recent glaciofluvial deposits. The high-quality data collected from this study support the case for a subglacial channel fill scenario. This case study presents a working model for re-entrant bedrock valley fills along the Niagara Escarpment that is compatible with evidence for meltwater flood deposits in the region (Kor and Cowell 1998; Sharpe et al. 2004). Whether this interpretation or alternative interpretations, such as preglacial subaerial deposition, will prevail in the buried-valley terrain of the Laurentian valley system, will require the collection of additional high-quality information and careful analysis of sparse data coverage.

From a hydrogeological perspective, it is interpreted that the deep aquifer system found in the valley bottom extends along the buried bedrock valley from the Niagara Escarpment in the west to the Bolton area in the east. Further, this preliminary assessment suggests that the deep aquifer may be continuous with the Bolton Aquifer, and is unlikely to be connected to either of the 2 currently utilized municipal aquifers in the Caledon East area. The proximity of the buried valley to the communities of Caledon East and Caledon makes it a potential target for additional municipal capacity. The coarse sediment in the deeper parts of the valley provides an approximately 30 m thick and 2 km wide target for hydraulic testing. Aquifer assessments will need to move to the hydraulic testing stage by establishing a series of monitors to be used in long-term pumping tests and for preliminary geochemical analysis.

Port Perry Tunnel Channel

The 2 seismic lines completed west (seismic line 1) and southwest (seismic line 2) of Port Perry in 2004 (*see* Figure 30.3) suggested the presence of a potential tunnel channel feature near the centre of seismic line 2. High-amplitude, inclined and crosscut reflectors were noted to extend to the bedrock reflectors in that area. Based on this seismic signal, this area was selected for drilling.

Borehole CAMC/YPDT-PP-4th Line (*see* Figure 30.3) was complete using a dual air rotary drill rig. The dual air rotary drilling system is an efficient drilling method to advance to depth without the use of heavy drilling "muds" (which can sometimes cause subsequent problems during well development and

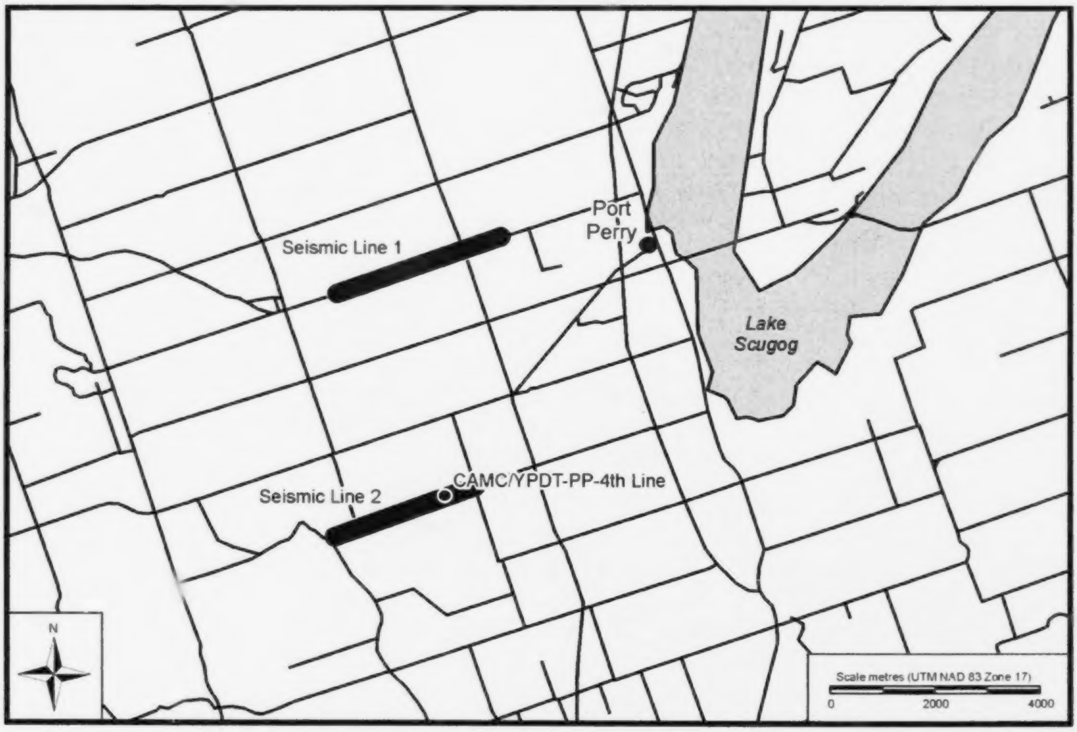


Figure 30.3. Locations of borehole CAMC/YPDT-PP-4th Line and 2 seismic lines near Port Perry.

production). The samples produced are disturbed "chip" samples and are reasonably representative of the cutting face at any given depth; however, they do not preserve any structure (Photo 30.1). As a result, this method is not as good as the PQ continuous coring system for determining detailed stratigraphy.

The detailed drilling log for Borehole CAMC/YPDT-PP-4th Line was not completed at the time of writing.

Preliminary analysis of samples obtained from borehole CAMC/YPDT-PP-4th Line indicate the potential for municipal water supplies within the tunnel channel. The results indicate the presence of 2 to 3 fining-upward sequences consistent with channel-fill sedimentation reported in boreholes to the east (Barnett et al. 1998). The lowest sequence begins at the bedrock surface at depth of 122 m, where a poorly sorted sand and gravel unit fines upwards to silty clay. The second major sequence occurs at a depth of 82 m where a sharp-based, approximately 20 m thick, very transmissive sand and gravel unit was observed. This sequence has potential for municipal water supply. This unit fined up to predominantly clayey silt at a depth of approximately 60 m. The last sequence is interpreted from depths of approximately 23 m to 6 m, where sand and gravel fine upward to silty clay. The upper 6 m of the borehole is interpreted as silty clay till. The data suggest that a large subglacial event eroded older sediments prior to depositing high to low energy deposits in several cycles.

Delineating the sediments along and across the channel length will be the subject of future investigations by the Region of Durham in their evaluation of this new potential municipal supply aquifer.

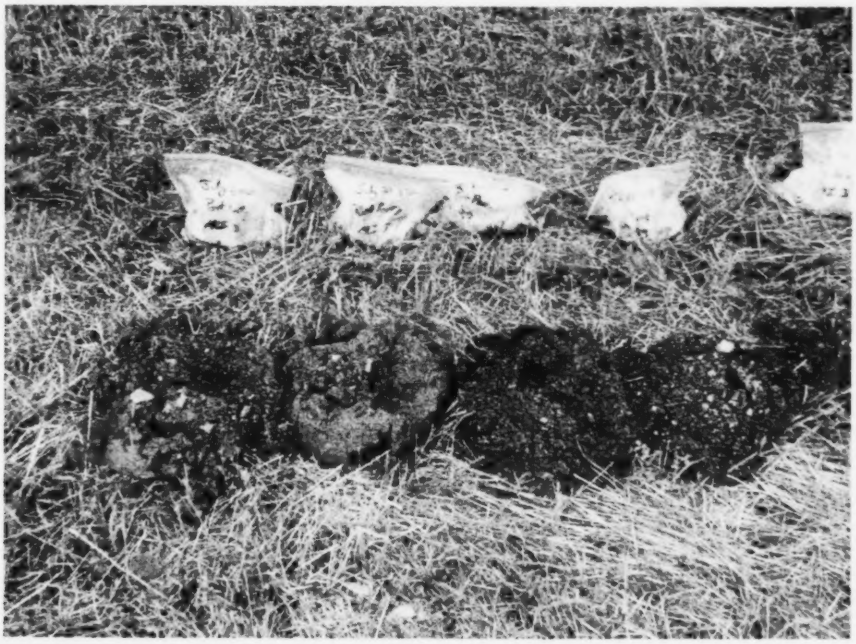


Photo 30.1. Samples obtained from the dual air rotary drilling of borehole CAMC/YPDT-PP-4th Line near Port Perry.

ONGOING AND FUTURE WORK

Additional borehole drilling to bedrock is being conducted in the Kempenfelt Bay area west of Barrie to follow up seismic survey results. The till uplands area north of the Oak Ridges Moraine is also under consideration for a PQ cored borehole to address questions regarding till stratigraphy in that area.

Additional downhole geophysics will be completed in monitoring wells installed by our regional municipalities within the CAMC area in 2004 and 2005. These surveys should help to further document the hydrostratigraphy across the area.

Additional seismic work will be conducted in the Rice Lake area across the location of a possible tunnel channel. The work will aid in the interpretation of the stratigraphy in the east side of the Oak Ridges Moraine, where little information is available.

REFERENCES

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Kenny, F.M. and Pugin, A. 1998. On the origins of the Oak Ridges Moraine; Canadian Journal of Earth Sciences, v.35, p.1152-1167.

Davies, S.D. and Holysh, S. 2004. Groundwater resource projects across the Oak Ridges Moraine; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.27-1 to 27-8.

Holysh, S., Davies, S.D. and Goodyear, D. 2004. An investigation into buried-valley aquifer systems in the Lake Simcoe area; *in* Summary of Field Work and Other Activities, 2004. Ontario Geological Survey, Open File Report 6145, p.28-1 to 28-6.

Kor, P.S.G. and D.W. Cowell. 1998. Evidence for catastrophic subglacial meltwater sheetflood events on the Bruce Peninsula, Ontario; Canadian Journal of Earth Sciences, v.35, p.1180-1202.

Russell, H.A.J., Arnott, R.W.C. and Sharpe, D.R. 2003. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada; Sedimentary Geology, v.160, p.33-55.

Scheidegger, A.E. 1980. The orientation of valley trends in Ontario; Zeitschrift für Geomorphologie, v.24, p.19-30.

Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J. and Pugin, A. 1996. Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models; Geological Survey of Canada, Current Research 1996-E, p.181-190.

Sharpe, D.R. and Russell, H.A.J. 2004. Basin analysis applied to modelling buried valleys in the Great Lakes Basin; *in* Three-dimensional geological mapping for groundwater applications workshops, Illinois State Geological Survey, Open File Series 2004-8, p.73-76.

Sharpe, D.R., Russell, H.A.J., Pullan, S.E. and Hunter, J.A. 2004. The character, sedimentary fill and hydrogeological setting of the buried Laurentian Valley, Nobleton Ontario; abstract, Geological Association of Canada–Mineralogical Association of Canada, Annual Meeting, May 12-14, 2004, St. Catharines, Ontario, Program with Abstracts, v.29, p.161.

Spencer, J.W. 1890. Origin of the basins of the Great Lakes of America; American Geologist, v.7, p.86-97.

Straw, A. 1968. Late Pleistocene erosion along the Niagara Escarpment of southern Ontario; Geological Society of America Bulletin, v.79, p.889-910.

31. Project Unit 04-030. Karst Delineation and Sinkhole Investigation in the Ausable Bayfield Conservation Authority Watershed and Surrounding Area

J. Hurley[1], A.G. Merry[1], F.R. Brunton[2], S. Wadley[1] and D. Abbey[3]

[1]Waterloo Hydrogeologic Inc., Waterloo, Ontario
[2]Sedimentary Geoscience Section, Ontario Geological Survey, Sudbury, Ontario
[3]AquaResource Inc., Waterloo, Ontario

INTRODUCTION

This paper reports on the study of the karst features and local sinkholes in the watershed of the Ausable Bayfield Conservation Authority and surrounding area (Figure 31.1). Portions of the watersheds of Upper Thames River and Maitland Valley conservation authorities are also part of the study area. The study was initiated by Ausable Bayfield Conservation Authority, in partnership with the Ontario Geological Survey (OGS) as part of its groundwater mapping program.

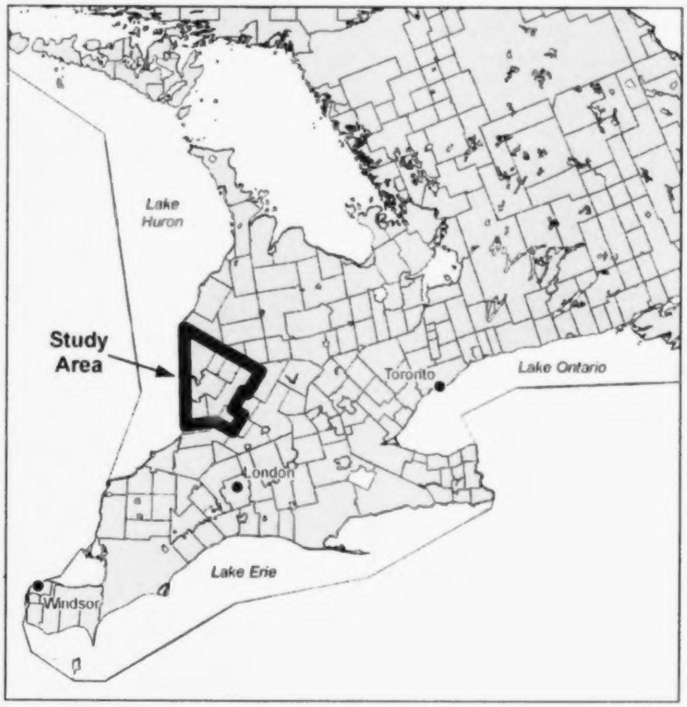


Figure 31.1. Location of study area.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.31-1 to 31-8.

© *Queen's Printer for Ontario, 2005*

A principal objective of this study was to investigate the contamination risk that the sinkholes pose to bedrock aquifers and local domestic water wells. Another objective was to study the hydraulic connection and groundwater flow paths between the sinkholes and the bedrock aquifers beneath the study area. It is important to delineate the extent of karst features to support source water protection initiatives within the watershed.

BACKGROUND

In 2003 and 2004, Waterloo Hydrogeologic Inc. was contracted to complete an initial sinkhole investigation in conjunction with the Ausable Bayfield Conservation Authority, the municipalities of West Perth and Huron East, and the Ministry of the Environment (Waterloo Hydrogeologic Inc. 2004). The study area is primarily agricultural, with intense cash crop farming and livestock operations. Surface runoff has been observed draining into sinkholes, posing a risk of potential contamination to underlying aquifers. Groundwater velocities in karst aquifers can be high and contaminants can be quickly transported to water wells with little attenuation. The study was initiated to improve the current understanding of the local surface water and groundwater conditions around sinkholes in the study area, with emphasis on sinkholes identified in the former townships of Hibbert and Tuckersmith.

The initial investigation involved a compilation and evaluation of regional and local groundwater information from the files of the municipalities of Huron East and West Perth. Within the study area, more than 50 sinkholes were identified, most of which occur in areas where bedrock is overlain by thin overburden. Regional groundwater surface mapping and information from water well records indicated that the karst features in bedrock extend over a much larger area than the surface expressions (i.e., sinkholes) suggest. It was also observed that groundwater surface elevations, as interpreted from water well records, are depressed by as much as 100 m in areas with karst features (Waterloo Hydrogeologic Inc. 2004). The depression in the groundwater level correlates with the mapped extent of Devonian Lucas Formation bedrock.

This study is a continuation of these sinkhole and karst investigations. Previous work under this project, including detailed mapping of sinkhole clusters and completion of a deep bedrock borehole near Hensall, is described by Abbey, Hurley and Merry (2004).

DRILLING PROGRAM FOR BRUSSELS MILL-1

In July 2004, borehole Hensall Road-1 was completed through bedrock near Hensall (Abbey, Hurley and Merry 2004). A second borehole, Brussels Mill-1, was completed in October 2004 in the community of Brussels. The location of borehole Brussels Mill-1 was chosen because the geological contact between the Lucas Formation and the overlying Dundee Formation is very close to ground surface beneath Brussels.

The overburden portion of the Brussels Mill-1 borehole (MOE well number A008116) was drilled and logged by W.D. Hopper and Sons Limited on October 1, 2004 using a DrillTech T-40-K rotary rig. Stainless steel casing was anchored into the upper, weathered portion of bedrock and grouted at a depth of 4.95 m. The contact between overburden and the weathered limestone bedrock was determined to be 3.5 m below ground surface. A pump test showed this well to produce less than 5.45 m^3/day.

Rock core drilling for Brussels Mill-1 began on October 12, 2004 using a CME 750 rotary drill rig outfitted for PQ (8.5 cm diameter) coring using a wireline system. Drilling was conducted by All-Terrain Drilling Limited. The borehole was completed on October 15, 2004, to 79.69 m below ground surface.

Table 31.1. Start-of-the-day water level measurements in borehole Brussels Mill-1 during drilling.

Date	Borehole Depth (m below ground surface)	Depth to Water in Open Borehole (m below ground surface)
October 12, 2004	4.95	4.73
October 13, 2004	15.23	Not measured
October 14, 2004	39.21	4.26
October 15, 2004	69.25	2.41

Continuous rock core was collected in 1.5 m flights from 4.95 to 79.69 m below ground surface. A high-resolution digital photograph of each 1.5 m core run was taken immediately after recovery of the rock core to provide a visual record of each depth interval.

As with the Hensall Road-1 well (Abbey, Hurley and Merry 2004), core recovery from Brussels Mill-1 was better than 95%. Losses occurred on a few occasions, usually when significant (>10 cm thick) poorly lithified or clay-rich zones were observed in the core or when problems were encountered with drilling.

In the Hensall Road-1 borehole, groundwater was encountered at a depth of 97.54 m. In the Brussels Mill-1 borehole, groundwater was encountered at much a shallower depth of 4.73 m. Table 31.1 catalogues the depth to static water level in the Brussels Mill-1 borehole as it was measured at the start of each drilling day. The measurements represent the hydraulic heads of the bedrock aquifer at progressively deeper intervals, so they provide some insight into vertical hydraulic gradients. Table 31.1 shows that, as borehole Brussels Mill-1 deepened, the static water level came closer to ground surface. This suggests that the bedrock aquifer has a significant upward hydraulic gradient.

The water levels recorded Brussels Mill-1 are comparable to levels recorded on Ministry of the Environment (MOE) well records for water wells in the area.

GEOLOGY OF THE BEDROCK DRILL CORE

The Brussels Mill-1 borehole was completed in October 2004. The Hensall Road-1 borehole was completed in July 2004. A total of 38 samples from the Brussels Mill-1 core and 25 samples from Hensall Road-1 core were collected for industrial minerals assessment, and detailed lithologic and petrographic analysis. The drill core from these boreholes provide insight into the Dundee and Lucas formational contact and into karst development in these rocks. The Hensall Road-1 core is also described by Abbey, Hurley and Merry (2004).

The Brussels Mill-1 borehole extended through most of the Lucas Formation, ending within a few metres of the estimated Amherstburg–Lucas formational contact. The Brussels Mill-1 core comprises approximately 6.7 m of coral-bearing, crinoidal packstone-grainstone limestones of the Dundee Formation, with the remaining core comprising variably dolomitized metre-scale sabkha cycles of the Lucas Formation. The contact between Dundee and Lucas formations is sharp in the Brussels Mill-1 core, with rip-up clasts of Lucas Formation dolostones present in the overlying Dundee Formation limestones. The placement of the Lucas–Dundee formational contact in the Hensall Road-1 is more difficult to define. Dundee lithofacies is evident several centimetres below the apparent contact. This is also observed in the bedrock section exposed near the mouth of the Maitland River at Goderich, where the usually sharp contact between Lucas Formation cyclic dolostones and the overlying fossiliferous limestones of the Dundee Formation is not easily discernible.

The Hensall Road-1 core appeared to be much more broken up than the Brussels Mill-1 core, with minor cavities and paleokarst brecciation evident. Surface-derived clay-soil material was present down to more than 30 m below the ground surface. The water table is also much deeper at this locality, with evidence of well-oxygenated waters and associated iron and manganese oxides present more than 79 m below the ground surface. In the Brussells Mill-1 core, the uppermost Lucas Formation shows evidence of paleokarst infilling. Paleokarst brecciation extends downward a few metres from the Lucas–Dundee formational contact (Photo 31.1).

Karstification of the Lucas Formation in both of the drill cores appears to be focussed along the contacts between various facies of the variably dolomitized metre-scale sabkha cycle. It appears to be most intense where the intertidal-supratidal top of a cycle is sharply capped by the next deeper water rock unit. Here, the rocks possess significant secondary porosity development and are extremely absorbent. This characteristic made it difficult to both wet the core down for more detailed examination of sedimentary textures and to apply dilute hydrochloric acid to differentiate dolostone from limestone lithofacies. The brecciated rock units, representing the anhydritic-rich and gypsiferous-rich portions of some sabkha depositional cycles, appear to have been most affected by karstification. Here, the potential for both lateral conduit groundwater flow and vertical hydraulic interconnectivity through the Lucas Formation are enhanced.

Karst development and groundwater conduit flow in southern Ontario is in the initial stages of study and documentation (e.g., Brunton, Dodge and Shirota, this volume; Worthington, Ford and Beddows 2000). Further work is required to delineate and characterize karst aquifers associated with the Dundee, Lucas and Amherstburg formations.

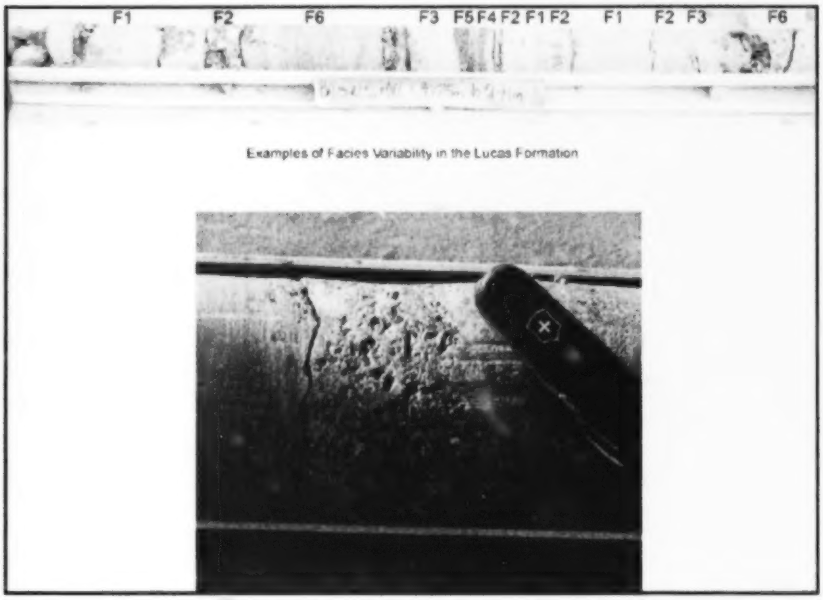


Photo 31.1. Examples of drill core from the Brussells Mill-1 borehole. The lower photo shows an example of a brecciated section of core in Lucas Formation rock.

CHISELHURST SINKHOLE SODIUM BROMIDE TRACER TEST

Tracer tests are a well-known method for investigating groundwater flow in karst aquifers (e.g., Ross, Rieg and Leibundgut 2001; Worthington 2003; Flury and Wai 2003). The exact locations and geometry of the conduits, caves, and solution-enhanced fractures in karst aquifers, which control groundwater flow, are usually not known in any detail. The traditional methods of groundwater investigation in non-karstic systems (such as pumping tests) are frequently of limited value in karst aquifers. The use of tracer tests is often the only direct method of obtaining information on hydraulic connections between wells, sinkholes and springs, and on groundwater flow directions and velocities.

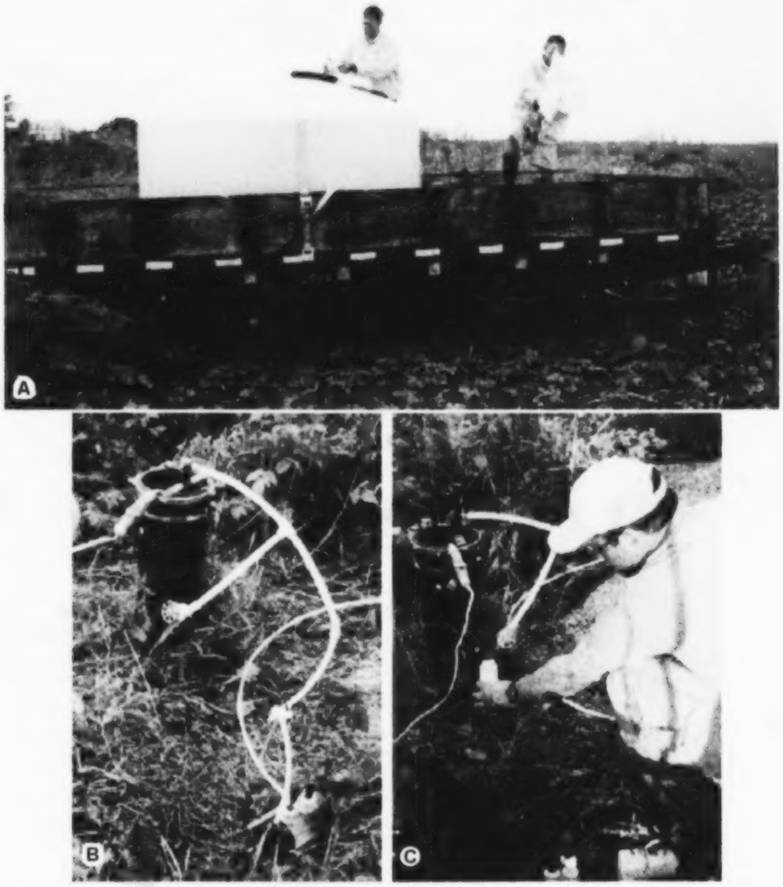


Photo 31.2. Sodium bromide tracer test at the Chiselhurst sinkhole location. A) Premixing the sodium bromide prior to the tracer release. B) Flow-through cell located at the Chiselhurst monitoring well. C) Taking a manual water sample from the Chiselhurst monitoring well.

A groundwater tracer study was undertaken at the Chiselhurst sinkhole, just west of Staffa in the south-central part of the study area. The principal objective of the tracer test was to better understand the degree of connectivity between sinkholes and both the shallow aquifer (20 to 40 m below ground surface) and the deep aquifer (100 m below ground surface) within the study area. Another important objective was to determine whether there is a hydraulic connection between the Chiselhurst sinkhole and local domestic water wells.

Sodium bromide was selected as the tracer for this study. Recent monitoring results from local domestic water wells show that bromide is not naturally present in groundwater in the study area. Sodium bromide is highly soluble, allowing relatively high concentrations of bromide to be introduced into groundwater (Photo 31.2A). Bromide is a conservative tracer, meaning it does not tend to precipitate or react with aquifer materials and it moves at the same velocity as groundwater (no retardation effect). Bromide tracers also allow the use of ion-selective electrodes to quickly measure bromide concentrations in a large number of water samples in real time. There are no known health risks associated with either sodium or bromide concentrations within the range being applied for this study.

The Orion 96-35 Ionplus™ bromide ion-selective electrode (ISE), affixed to an Orion 5-Star portable multimeter, was used to monitor bromide concentrations in the field during the tracer study. The use of the bromide electrode allows real-time analysis of groundwater samples to help quickly track the progress of the tracer plume once it is detected. The bromide electrode has a calibration range of 1×10^{-6} to 1 moles of bromide, which is equivalent to a concentration range of approximately 0.40 to 80 000 mg/L of bromide. However, the practical field detection limit for the electrode was around 1 mg/L. This takes into account field variables such as temperature, hand mixing of samples (as opposed to the use of magnetic stir bars), and non-correction of variances in ionic strength.

The ion-selective bromide electrode was calibrated using a standard stock solution of 1000 mg/L bromide provided by the University of Waterloo. The electrode was then attached to the flow-through cell (Photo 31.2B) and tested to ensure that all was in working order.

A flow-through cell was installed at the monitoring well at Chiselhurst (*see* Photo 31.2B) to enable continuous monitoring of groundwater for the first 5 days of the tracer test. The flow-through cell allows for the in-line analysis of water as it is pumped from the well. The flow-through cell consists of a clear acrylic cylinder with a high-density polyethylene (HDPE) cap and base sealed in place with O-rings and a bracket.

The tracer test was initiated the afternoon of Tuesday, June 21, 2005. Prior to release of the tracer, a submersible Grundfos$^{\text{TM}}$ pump was affixed to the Chiselhurst monitoring well and tested. A portable 3785 L water tank was used to prepare the sodium bromide solution (*see* Photo 31.2A). The water tank was placed as close to the Chiselhurst sinkhole as possible, on the edge of the adjacent field. The water tank was filled with approximately 3500 L of potable water. A total mass of 182 kg of photo-grade (99.5% pure) sodium bromide salt in a fine granular form was added to the water tank. A ditch pump and hose were used to pump water from the base to the top of the tank to encourage dissolution of the salt and mix the solution.

The amount of salt added to the tank provided a solution with an average bromide concentration of approximately 38 000 mg/L. The practical field detection limit for the ion selective bromide electrode is 1 mg/L, meaning that bromide concentrations in groundwater could potentially be diluted by more than 4 orders of magnitude and still be detected by the electrode. A sample of the bromide solution taken from the top of the water tank and submitted to a private lab for analysis had a bromide concentration of 26 200 mg/L.

Table 31.2. Discussion of possible scenarios to explain why bromide tracer has not yet been detected in the monitoring well network.

Potential Scenario	Discussion
Tracer has not travelled far enough from the release point to be detected.	This is very unlikely. Groundwater flow in the conduits is expected to be in the range of >100 m per day. During the first 50 days, the tracer is expected to have moved more than 5 km.
Tracer has been diluted through mixing with native groundwater causing concentrations to be below detection limits.	This is very unlikely. A concentration reduction of nearly five orders of magnitude would be required to achieve non-detect results with the bromide probe.
The bromide specific probe did not work properly.	This is very unlikely. The probe was calibrated regularly during the tracer test and was able to detect stock samples with a high level of accuracy.
Tracer moved through conduits above the water table, circumventing our monitoring network.	This is possible, but unlikely. Beneath the Chiselhurst sinkhole, there is approximately 100 m of Dundee and Lucas formations rock that is unsaturated or perched. Conduits oriented along the bedding within rock could result in transport of the tracer beyond our monitoring network. It is more likely that solution-enhanced conduits would be more concentrated near the sinkhole and would not extend laterally in the unsaturated dolostone and limestone.
Tracer moved through a conduit, or conduits, that was not intersected by our monitoring wells.	This is the most likely explanation. Conduit flow within karst systems is generally complex and difficult to predict. The route followed by the bromide plume may have been very discrete, bypassing the monitoring wells.
Tracer moved so quickly that the peak concentration and recession were not sampled.	This is unlikely. Samples were collected regularly and very frequently during the initial phase of the test. Even though conduit flow is believed to be very rapid, it is unlikely that a tracer plume with such a high initial concentration would have "flushed" through the system undetected if it had intersected a monitoring well.

The sodium bromide solution was released to the sinkhole by running the hose from the water tank to the sinkhole and pumping the solution using the ditch pump. The release occurred at 6:30 pm and took 9 minutes. At the time of the tracer release, a small creek that drains into the sinkhole had an estimated maximum flow of around 2 L per minute. A tile drain that terminates at the sinkhole had a measured flow of 39 L per minute. A sample of the tile drain water was collected just prior to the release of the tracer and submitted for analysis.

A light rainfall occurred immediately prior to the tracer release. The precipitation record obtained from the meteorological station in Exeter noted that 7.6 mm of rainfall occurred that day. This rainfall was not enough to cause visible surface runoff at the release location, and did not appear to increase flow in either the tile drain or the small creek that drain into the sinkhole.

Bromide concentrations were monitored continuously for the first 5 days after the tracer release (Photo 31.2C). Additionally, groundwater samples were taken and analyzed from 10 domestic water wells surrounding the sinkhole. Wells were sampled approximately twice each hour. After the first 5 days of monitoring, the sampling frequency was reduced to once per day for the remainder of the month and then to 3 times per week for the following 2 months.

Bromide was not detected at any of the monitoring wells during the tracer test. Due to the large mass of sodium bromide introduced at the sinkhole, it is hypothesized that the bromide plume from the sinkhole did not intercept any monitoring wells. Other potential scenarios are discussed in Table 31.2.

Although the bromide tracer was not detected, this should not be interpreted as evidence that there is no hydraulic connection between water that enters the groundwater system via sinkholes and nearby domestic water wells. This tracer test represents a "snapshot" in time. There are a number of explanations for why the tracer was not detected in the monitoring wells (*see* Table 31.2). The hydraulics of this karst system may also differ significantly under different environmental conditions (e.g., drought conditions, significant rainfall events, spring freshet, seasonal fluctuations in water table). Additionally, excessive water usage may cause a water well to "capture" a contaminant plume emanating from a sinkhole.

REFERENCES

Abbey, D., Hurley, J. and Merry, A.G. 2004. Sinkhole investigation in the Ausable Bayfield Conservation Authority watershed and surrounding area; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.29-1 to 29-6.

Flury, M. and Wai, N.N. 2003. Dyes as tracers for vadose zone hydrology; Reviews of Geophysics, v.41, p.2-1 to 2-37.

Ross, J.H., Rieg, A. and Leibundgut, C. 2001. Tracer study on the tectonic control of the drainage system in the contact karst zone of Lake Vorlap (Swiss Alps); Acta Carsologica, v.30/2, p.203-213.

Waterloo Hydrogeologic Inc. 2004. Sinkhole investigation for areas mainly within the municipalities of Huron East and West Perth; unpublished report, Waterloo Hydrogeologic Inc., Waterloo, Ontario, 105p.

Worthington, S.R.H. 2003. A comprehensive strategy for understanding flow in carbonate aquifers; *in* Karst Modeling, The Karst Waters Institute, Charles Town, West Virginia, Special Publication 5, p.30-37.

Worthington, S.R.H., Ford, D.C. and Beddows, P.A. 2000. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution; *in* Speleogenesis: evolution of karst aquifers; National Speleological Society, Huntsville, Alabama, p.463-472.

32. Project Unit 05-016. Groundwater Resource Project for the Halton Area Watershed, Southern Ontario

D. Gale[1] and P. Sarvas[2]

[1]Conservation Halton, Milton, Ontario
[2]Sedimentary Geoscience Section, Ontario Geological Survey, Sudbury, Ontario

---

INTRODUCTION

In partnership with the Ontario Geological Survey, Conservation Halton has undertaken a study to delineate and characterize the groundwater resources of its watershed area (Figure 32.1). This study will assist in establishing an effective source water protection plan for this area.

The Conservation Halton watershed area is 948 km^2. It includes a segment of the Niagara Escarpment and 17 watercourses that drain into Lake Ontario (*see* Figure 32.1). The communities of Burlington, Oakville, Milton, Halton Hills and Flamborough are found within its boundaries.

BACKGROUND

There are 2 significant aquifer types in the Conservation Halton watershed area: the dolostones of the Amabel and Guelph formations in the uplands to the west of the Niagara Escarpment, and the sand- and gravel-filled bedrock valley systems on both sides of the Niagara Escarpment (Figure 32.2). Recent

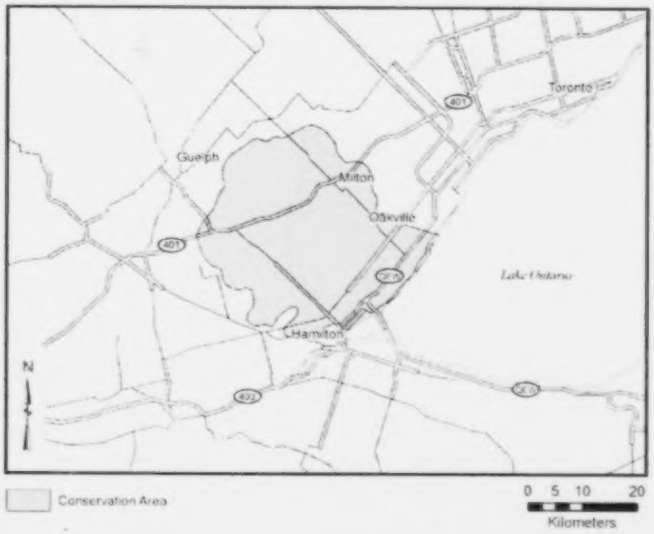


Figure 32.1. Location of the Conservation Halton watershed area.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.32-1 to 32-4.

© Queen's Printer for Ontario, 2005

studies (e.g., Holysh, Davies and Goodyear 2004; Russell et. al. 2004) have identified the potential of buried bedrock valleys as regional high-yield aquifers. Buried bedrock valley aquifers are often protected from surface contamination by a large thickness of relatively low-permeability confining layer.

Recent groundwater studies in and near the Conservation Halton watershed (e.g., Holysh 1997; SNC Lavalin Engineers & Constructors 2004) have utilized data from the Ministry of Environment's (MOE) Water Well Information System (WWIS) database. However, water well records from the WWIS provide sparse information for delineating the depth to bedrock within the study area. As a result, the depth to bedrock and the extent of buried bedrock valley aquifers within Conservation Halton's watershed are still poorly understood.

SCOPE OF STUDY

The primary objective of this project is to collect, correct, interpolate and interpret existing data to characterize groundwater resources of the Conservation Halton watershed. Principal products include creation of a geographic information system (GIS)-based groundwater resource database, generation of a set of hydrogeology maps, development of a three-dimensional geological model, interpretation of the watershed's groundwater resources within a geological and stratigraphic framework, delineation of buried bedrock valleys and initial characterization of aquifer productivity and ambient groundwater quality.

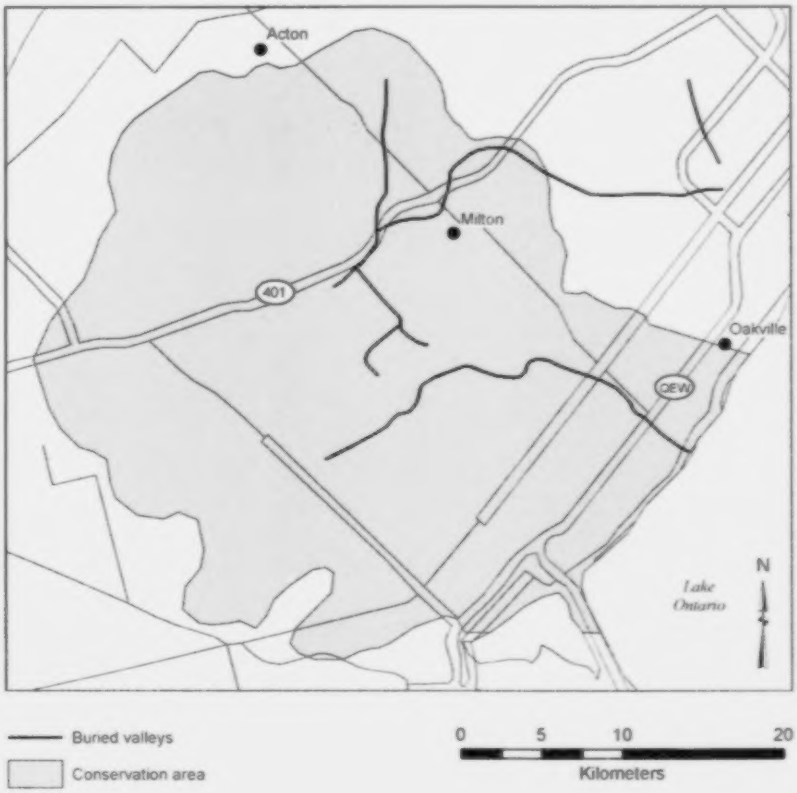


Figure 32.2. Locations of interpreted buried bedrock valleys in the Halton region watershed (*modified after* Holysh 1997).

Development of a Groundwater Resource Database

A robust GIS-based groundwater resource database for the Conservation Halton watershed area will be developed upon the existing WWIS database. The current WWIS database contains numerous water wells with unreliable location co-ordinates (as identified by MOE criteria). To verify or correct these co-ordinates, both a desktop and a field location program will be conducted to locate these wells and obtain accurate locations utilizing Universal Transverse Mercator (UTM) co-ordinates.

In addition to using the WWIS database, data from other subsurface investigations in the study area, such as, where possible, oil and gas wells, geotechnical boreholes, subdivision developments, landfills and aggregate operations, will be obtained. Data obtained from these sources are generally considered to be of higher quality than the WWIS data because they have accurate UTM locations and because a professional geoscientist or engineer generally logs the boreholes.

Generation of Hydrogeological Maps

The updated groundwater resource database will then be used to generate a set of hydrogeological maps. Point data from the database will be interpolated to generate the following two-dimensional 'surfaces':

- Overburden thickness
- Sand and gravel thickness
- Bedrock surface topography
- Water table surface
- Depth to water table
- Depth to first aquifer
- Potentiometric surface
- Vertical hydraulic gradients
- Potential discharge and recharge areas
- Aquifer vulnerability

Development of a Conceptual Geological Model

The hydrogeological maps will be correlated with geological maps of the watershed area and evaluated to develop a three-dimensional conceptual model of the geology and stratigraphy. Regional hydrogeological features will be interpreted within a geological framework. Overburden aquifers and aquitards will be correlated with surficial geological features (such as moraines, kames and glaciolacustrine plains). Bedrock aquifers will be correlated with bedrock features (such as regional bedrock formations and karst structures). Other hydrogeological parameters (such as groundwater flow paths, and recharge and discharge areas) will be correlated with regional physiography (such as upland areas, surface drainage systems and wetlands).

Delineation of Buried Bedrock Valleys

Bedrock surface topography will be evaluated to further delineate buried bedrock valleys within the watershed. Previous studies (e.g., Holysh 1997; SNC Lavalin Engineers & Constructors 2004) have provided a preliminary delineation of many buried valleys; however, better characterization is required for effective groundwater resource management.

The Aquifer Management Plan for the Regional Municipality of Halton (Holysh 1997) identifies a number of buried bedrock valleys that require further investigation (*see* Figure 32.2). A buried bedrock valley system extends northwest from the top of Walkers Line at Nassagaweya Canyon, west of Milton. Water quality data suggest that this system may be affecting the Region of Halton's municipal wells at Walkers Line. Further study is required to establish this possible hydraulic connection.

A second buried bedrock valley system trends eastward beneath the communities of Campbellville and Kelso, northwest of Milton. It is believed to eventually connect with a larger buried valley system to the southeast, but further study is required to delineate this connection.

Lastly, a buried bedrock valley system may connect aquifers beneath the Black Creek watershed and the Sixteen Mile Creek watershed near the community of Limehouse (close to Acton). Further study is required to delineate this buried valley and to establish the direction of groundwater flow.

A field-oriented study, similar to investigations of Laurentian Channel buried-valley aquifers in southern Ontario, which include seismic profiling and deep borehole drill (e.g., Russell et al. 2004; Holysh, Davies and Goodyear 2004), is beyond the scope of this study. Instead, buried valleys will be investigated and delineated through the incorporation of existing high-quality well data (e.g., geotechnical boreholes, oil and gas well records, monitoring well logs) into the groundwater resource database.

Charactizing Ambient Groundwater Quality and Aquifer Productivity

In addition, information from the groundwater resource database will be evaluated to characterize ambient groundwater quality and productivity of aquifers within the watershed. Water quality information from the WWIS is based on the subjective observations of well contractors upon completion of the water well. Wherever possible, these data will be augmented with pre-existing laboratory analyses of groundwater samples from wells within the watershed area.

REFERENCES

Holysh, S. 1997. Halton aquifer management plan, Phase 2 report, Muncipal wellhead protection program technical study; unpublished report, Regional Municipality of Halton, 170p.

Holysh, S., Davies, S.D. and Goodyear, D. 2004. An investigation into buried valley aquifer systems in the Lake Simcoe area; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.28-1 to 28-6.

Russell, H.A.J., Pullan, S.E., Hunter, J.A., Sharpe, D.R. and Holysh, S. 2004. Buried valley aquifers: delineation and characterization from reflection seismic and core data at Caledon East, Ontario; *in* Geological models for groundwater flow modeling, workshop extended abstracts, Illinois State Geological Survey, Open File 2004-8.

SNC Lavalin Engineers & Constructors 2004. Groundwater resources characterization and wellhead protection partnership study, draft report to City of Hamilton; unpublished draft report, SNC Lavalin Engineers & Constructors, 168p.

33. Project Unit 04-029. Conceptualization and Calibration of a Three-Dimensional Groundwater Flow Model for the Watersheds in Southwestern Ontario

A.G. Merry[1] and L.P. Nicks[2]

[1]Waterloo Hydrogeologic Inc., Waterloo, Ontario
[2]Upper Thames River Conservation Authority, London, Ontario

INTRODUCTION

Under the groundwater mapping program of the Ontario Geological Survey, a groundwater flow model is being developed for the watersheds of the Ausable Bayfield, Upper Thames River, Lower Thames Valley, Maitland Valley, Essex Region and St. Clair Region conservation authorities in southwestern Ontario. The project involves the development of three-dimensional conceptual geologic and hydrogeologic models and the development, calibration, and application of a FEFLOW® groundwater flow model.

The study area is located in southwestern Ontario approximately 200 km east of Toronto (Figure 33.1). Over 1.2 million people reside within the 20 000 km^2 study area, which is bound to the west by Lake Huron, and to the south by Lake Erie and Lake St. Clair. The study area includes several watersheds managed by the 6 conservation authorities. The numerous rivers and streams within these watersheds drain into Lake Huron, Lake St. Clair or Lake Erie. The study area is characterized by intensive agriculture and by industry concentrated primarily in urban areas (Sarnia, Windsor, London and Stratford).

Recently, the Ontario Ministry of the Environment (MOE) funded a series of regional groundwater studies across Ontario. These groundwater studies were completed between 2000 and 2003, and several of these studies were completed in various areas within each of the jurisdictions of the 6 conservation authorities (e.g., Golder Associates 2001; Waterloo Hydrogeologic Inc. 2001; International Water Consultants 2003; Dillon Consulting Limited and Golder Associates 2004a, 2004b). A key accomplishment of these studies was the characterization of the geological and hydrogeological settings and the development of regional mapping products. During many of the regional studies, it was apparent that groundwater flow does not always follow surface watersheds. This is particularly true in karstic and deep, confined bedrock aquifers, such as those present in the Dundee and Lucas formations that underlie the study area.

OBJECTIVES

The purpose of this study is to improve the current understanding of the groundwater flow system, including the linkages between deep regional bedrock aquifers and the shallow groundwater system. Based on the work conducted during regional groundwater studies, it is understood that groundwater flow paths in the deep groundwater system cross watershed boundaries, necessitating the regional approach

---

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.33-1 to 33-5.

© Queen's Printer for Ontario, 2005

adopted for this study. Understanding these processes is required to assess impacts to the ground or surface water regimes that may occur either locally or regionally.

The focus of this report is the development of the conceptual model for the three-dimensional geologic and hydrogeologic models. The development, calibration, and application of a computer-derived numerical groundwater flow model for the entire study area will be completed during the fall of 2005.

GEOLOGIC AND HYDROGEOLOGIC CONCEPTUALIZATION

The construction of the groundwater flow model, using the software package FEFLOW®[1], is based on the geologic and hydrogeologic conceptualization. The development of the geologic and hydrogeologic conceptual model for the 6 conservation authorities has built upon studies previously completed by the Ontario Geological Survey, Geological Survey of Canada, private consulting companies, and conservation authorities. A large component of the study is the review of these previously conducted studies and compilation of the data into a common geographic information system (GIS)-based database. This is necessary to create seamless mapping products across the study area, which is required for the development of the hydrogeologic model. The MOE's Water Well Information System (WWIS) is one of the primary data sources for the study.

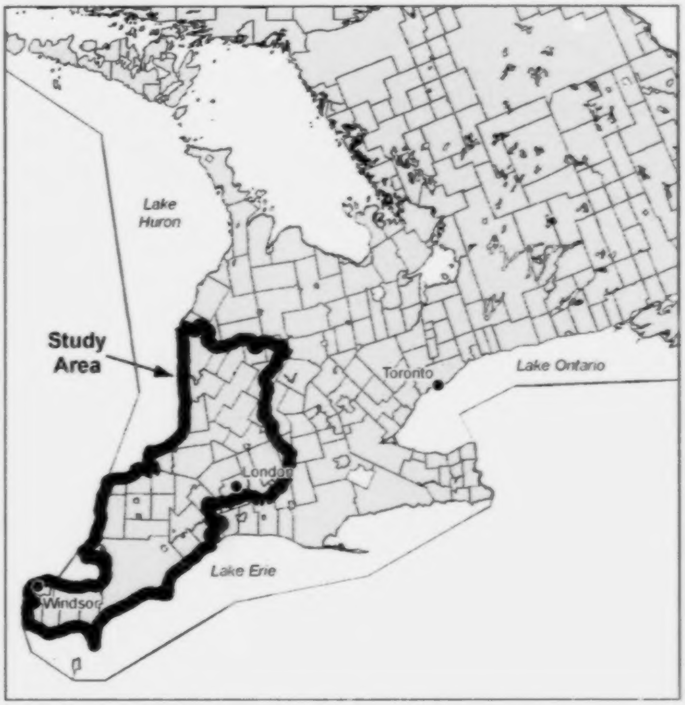


Figure 33.1. Location of study area.

---

[1] FEFLOW® Finite Element Subsurface FLOW System, version 5.106. FEFLOW is copyright (2005) and is a registered trademark of WASY GmbH (Institute for Water Resources Planning and Systems Research), Berlin-Bohnsdorf, Germany.

The distribution of bedrock and overburden wells contained within the WWIS are shown in Figure 33.2. Over 100 000 wells exist within the study area.

Other data sources that have been compiled during this project include the following:

- Digital elevation model (DEM)
- Stream locations
- Geophysical logs
- Quaternary geology reports and maps
- Surface water modelling results and recharge estimates
- Stream gauge and spot flow locations and monitoring data
- Orthoimagery
- Land use and cover
- Permits to Take Water
- Strahler Stream Order Number
- Oil and gas well records
- Bedrock geology reports and maps
- Numerical groundwater models completed from smaller local-scale projects
- Groundwater levels from the MOE's Provincial Groundwater Monitoring Network (PGMN) and other monitoring programs
- The Ontario Ministry of Natural Resources' NRVIS base maps
- Wetlands, ESA's, and Areas of Natural Scientific Interest (ANSI's)

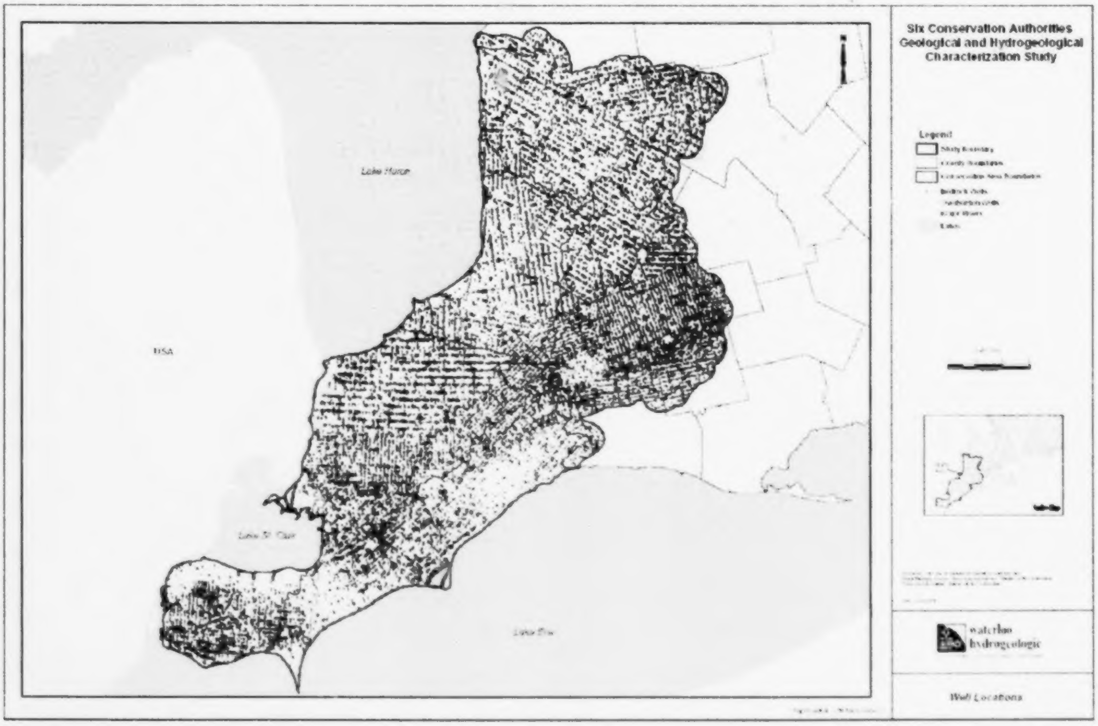

Six Conservation Authorities
Geological and Hydrogeological
Characterization Study
Legend
Lake Huron
USA
Lake St. Clair
Lake Erie
waterloo hydrogeologic
Well Locations

Figure 33.2. Locations of water wells in the study area (from Ontario Ministry of Environment Water Well Information System database).

To obtain an understanding of the hydrostratigraphic conditions and to construct the conceptual geological model within the study area, 12 regional geological cross-sections were developed. Following interpretation of the regional cross-sections, 109 smaller scale cross-sections (oriented north-south and east-west) were drawn and interpreted across the study area. The intersecting cross-sections were spaced using a 10 km grid, and all cross-sections were less than 40 km in length. These smaller scale cross-sections provided the basis for construction of the conceptual hydrostratigraphic units that define the layers and parameter distributions (e.g., hydraulic conductivity) for the numerical model. An additional 84 local-scale cross-sections were also drawn to examine the spatial extent of intermediate sand and gravel units within kame moraines and intermediate aquifers, and to examine areas where buried bedrock valleys had been previously reported.

The cross-sections were interpreted with the selection of geologic contact picks using the following simplified 6 layer conceptual model for the study area:

- Upper aquifer
- Upper till(s) (St. Josephs, Elma, Stratford, Mornington, Wartburg and Rannoch tills)
- Intermediate aquifer
- Intermediate till(s) (Tavistock and Port Stanley tills)
- Lower aquifer
- Lower till(s) (Catfish Creek and Canning tills)

In areas where extensive lacustrine clay deposits are present (such as the St. Clair Clay Plain), this feature was incorporated into the appropriate conceptual layer. This approach was adopted to facilitate groundwater model development, and was considered appropriate due to the hydrogeologic similarities between the fine-grained tills and lacustrine deposits.

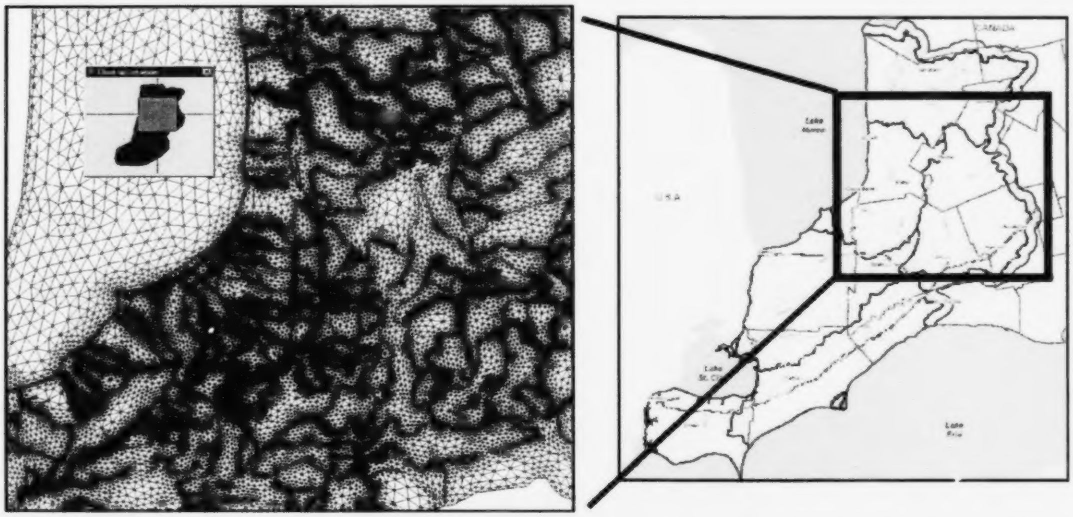


Figure 33.3. Finite element mesh of the FEFLOW® groundwater flow model in the north part of the study area, showing mesh refinements at streams and beneath Lake Huron.

FEFLOW® GROUNDWATER FLOW MODEL

The FEFLOW® groundwater flow model has been constructed and is currently being calibrated. The finite element mesh that was developed for the model was designed to align with relevant streams and rivers throughout the study area. The mesh is designed to be finer in areas of interest (i.e., near streams). Figure 33.3 illustrates the refinement at streams and beneath Lake Huron. The layers that have been interpreted through the development of cross-sections have been used to define layer elevations within the groundwater flow model. Parameter values and recharge rates have been assigned within the model based on interpreted locations of aquifers and aquitards and existing surficial geology mapping.

FUTURE WORK

It is intended that the FEFLOW® groundwater flow model calibration and simulation of predictive scenarios will be completed during the fall of 2005. The calibrated model will be applied to assess groundwater flow rates and water budget components for each of the 6 conservation authorities within the study area. The model will also be used to evaluate different scenarios, which may include drought conditions, urbanization, changes in agricultural practices, and increased groundwater usage.

REFERENCES

Dillon Consulting Limited and Golder Associates 2004a. Middlesex–Elgin groundwater study final report, File 02-0394; unpublished report, Dillon Consulting Limited and Golder Associates, London, Ontario, 155p.

——— 2004b. Lambton County groundwater study final draft report, Project 03-2434; unpublished report, Dillon Consulting Limited and Golder Associates, London, Ontario, 140p.

Golder Associates 2001. Phase II groundwater protection study, county of Oxford; unpublished report, Golder Associates, Mississauga, Ontario, 189p.

International Water Consultants 2003. Huron County groundwater study; unpublished report, International Water Consultants, Newmarket, Ontario, 82p.

Waterloo Hydrogeologic Inc. 2001. Perth County groundwater study; unpublished report, Waterloo Hydrogeologic Inc., Waterloo, Ontario, 142p.

34. Project Unit 05-015. Sedimentary Geoscience Section Metadata Project

P.A. Takats[1], **M.G. Easton**[2], **E.G. Drouin**[1], **D.J. Scholtz**[1] **and J.W. Boyd**[3]

[1]Sedimentary Geoscience Section, Ontario Geological Survey
[2]Publication Services Section, Ontario Geological Survey
[3]Information and Marketing Services Section, Ontario Geological Survey

PREFACE

The objective of the Sedimentary Geoscience Section (SGS) metadata project is to create metadata records for SGS publications published by the Ontario Geological Survey (OGS) prior to December 2004.

INTRODUCTION

The OGS, Ministry of Northern Development and Mines (MNDM), has a long history of producing quality geoscience publications. Since 1890, over 13 500 publications have been released and the volume of publications continues to grow.

These publications comprise geospatially referenced data (i.e., information based on a geographic area, rather than a general topic not limited to a specific geographic area). The Mines and Minerals Division of MNDM, which includes the OGS, has long used geospatial technologies for retrieval and transmission of geological information and for the administration of Ontario's mining lands (i.e., CLAIMaps) (Romani and Dumont 2002).

This large volume of publications requires a system that allows fast discovery of relevant publications and also provides efficient management of this information resource. The system currently in use, the "Publications Database", which resides in an Oracle® relational database, incorporates all OGS publications. The system has search, retrieval and viewing capabilities accessible through the Earth Resources and Mineral Exploration webSite (ERMES) (http://www.mndm.gov.on.ca/mndm/mines/ermes/default_e.asp).

However, a complementary avenue of approach to this wealth of information is through the use of "metadata" or "metadata records".

WHAT ARE METADATA?

At its most basic level, "metadata" are "information about data or other information" or, more simply, "information about information". "Formal Metadata" are metadata that follow an approved standard (originally established by the US Federal Geographic Data Committee) that provides, through formally structured documentation, a common set of terminology, definitions, and information about values to be provided. By describing the "who, what, where, when, why, and how" of every aspect of the data, formal metadata help organize and maintain an organization's internal investment in data, provide

---

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.34-1 to 34-7.

© Queen's Printer for Ontario, 2005

information to data catalogues and clearinghouses, and provide information to aid data transfers (http://walrus.wr.usgs.gov/infobank/programs/html/definition/fmeta.html; http://geology.usgs.gov/tools/metadata/tools/doc/faq.html [accessed October 6, 2005]).

The Ontario Government developed a metadata standard (GO-ITS 72.0: Government of Ontario 1996), based on Federal Geographic Data Committee standards, for the description of the various databases and information holdings that a ministry or agency collects, uses and/or distributes. The objectives of the standard are to

1. increase internal and public awareness of what information holdings (data sets) the various ministries and associated agencies hold;
2. improve information sharing and customer service;
3. promote a consistent recording and use of Geospatial Metadata;
4. reduce duplication of work and data storage.

The information in metadata is more comprehensive than a simple citation (title, year, publication title). The categories in a metadata record contain more detailed information, such as the type of data, the year the data were collected, the number of samples collected, geospatial information (e.g., Universal Transverse Mercator (UTM) coordinates, or longitude and latitude etc.). Metadata records allow information about a publication to be more readily accessible to Internet search applications. In such a search, the metadata record rather than the actual information holding is retrieved. In addition, applications with geospatial searching capabilities can search through the database for metadata with matching geospatial coordinates. Once a search is completed, the client can scroll through the list of retrieved metadata records and, based on the information within each record, decide which publication is relevant to their requirements. The actual publication itself can then be located from the source identified within the metadata record.

BACKGROUND

The Ontario Geological Survey committed to using metadata records in the fall of 2001. The original intent for the creation of metadata records was to improve the discovery of OGS publications and to make that information more accessible to MNDM's clients and stakeholders. Originally, metadata records were created only for digital publications; mainly large data sets obtained as a result of geochemical and geophysical surveys. These data sets were released in the Miscellaneous Release—Data (MRD) or the Geophysical Data Set (GDS [formerly ERLIS Data Set]) series of publications.

In the fall of 2004, the Mines and Minerals Division (including OGS) decided to extend the scope of metadata to encompass current and historical non-digital publications. All authors were required to create metadata records for all their new work published by the OGS. In addition, each OGS staff member was provided with a list[4] of their past OGS publications and requested to complete metadata records for these publications by end of the fiscal year (March 31, 2005).

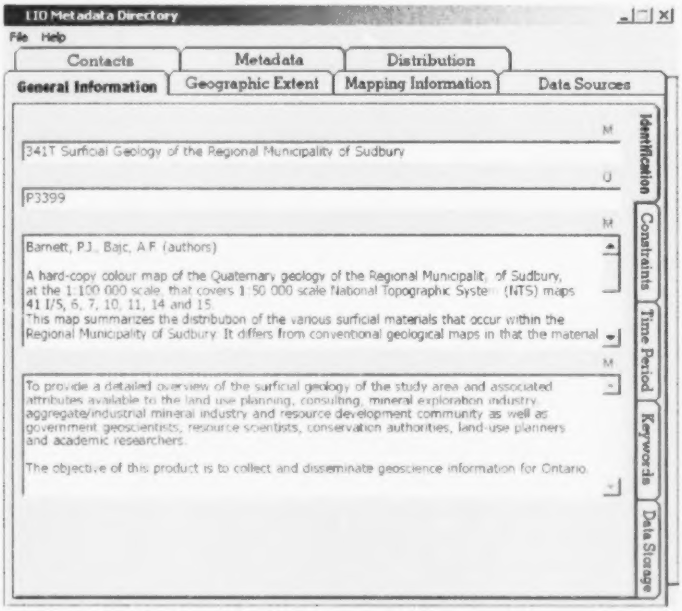
As mentioned earlier, there are over 13 500 OGS publications spanning the time period from 1890 to 2004; however, there are actually closer to 17 500 items for which metadata records are required. The difference is due to the inclusion of individual chapters or articles from various compendia volumes published by OGS (i.e., Special Volumes; *Annual Reports*; *Summary of Field Work and Other Activities* and *Report of Activities* volumes (both of the latter have been published in the Miscellaneous Paper and Open File Report series)).

---

[4] A Microsoft® Excel spreadsheet was created from information in the Oracle® database; subsets were generated for individual authors and later for the SGS-author list. Critical to later use of the metadata in information searches are that the title and the acronym for the publication in the metadata record match exactly that in the Publications Database; hence, the provision of the Excel spreadsheet to the authors (as mentioned in "Project Design and Implementation").

Prior to 2004, OGS authors were required at the time of publication to create metadata records only for MRD and GDS publications. The authors completed a Microsoft® Word template containing the representative categories of the metadata record. This information was then transferred into the appropriate fields of a metadata record following editorial review by Publication Services Section staff. The metadata record was then added to the Land Information Ontario (LIO) metadata database (see below).

The decision in 2004 to create metadata for all OGS publications made this multi-step method impractical. To streamline this process, a decision was made that authors would enter information directly into a database using the LIO metadata directory entry tool. The LIO metadata directory entry tool is normally only accessible to the custodian of the metadata database; however, due to the large volume of metadata records to be created, all authors were given access to the program, the software for which was installed on their office computer. In November 2004, training sessions were organized to instruct authors in using the LIO metadata directory entry tool (user interface for database entry) (Figure 34.1). The authors were required to attend 1 of 3 training sessions intended to assist the authors with generating their own metadata records; on-going individual assistance has been available as required. When completed by the authors, the records are reviewed by an editor in the Publication Services Section and then by the Geoscience Data Specialist in the Information and Marketing Services Section. Completed and reviewed metadata records are incorporated into a new MNDM metadata database, which are then uploaded to the Ontario Land Information Directory.



341T Surficial Geology of the Regional Municipality of Sudbury

P3399

Barnett, P.J., Bajc, A.F. (authors)

A hard-copy colour map of the Quaternary geology of the Regional Municipality of Sudbury, at the 1:100 000 scale, that covers 1:50 000 scale National Topographic System (NTS) maps 41 I/5, 6, 7, 10, 11, 14 and 15.
This map summarizes the distribution of the various surficial materials that occur within the Regional Municipality of Sudbury. It differs from conventional geological maps in that the material

To provide a detailed overview of the surficial geology of the study area and associated attributes available to the land use planning, consulting, mineral exploration industry, aggregate/industrial mineral industry and resource development community as well as government geoscientists, resource scientists, conservation authorities, land-use planners and academic researchers.

The objective of this product is to collect and disseminate geoscience information for Ontario.

Figure 34.1. The main page of a completed metadata record for a Quaternary geology map as viewed using the LIO Metadata Directory entry tool user interface provided to OGS authors to create metadata records.

The Ontario Land Information Directory (OLID: http://www.lio.mnr.gov.on.ca) is housed in the Land Information Ontario (LIO) Warehouse established by the Government of Ontario to orchestrate the collection and management of land information in the Province of Ontario. The Ministry of Natural Resources (MNR) led the initiative in 1998 to create the infrastructure and now administers the searchable tools, the data sets and the metadata databases. OLID was designed specifically to capture all of Ontario's "geospatial" metadata across various ministries, agencies, boards, commissions and private sector partners. It is one of an international network of Web-based geospatial metadata directories, which conform to the national and international standards (mentioned previously). OLID is accessible by the public via the Internet at the MNR's OLID metadata search Web page (http://lioapp.lrc.gov.on.ca/edwin/edwin.asp [accessed October 6, 2005]). It has Web-based geographic and keyword search capabilities that enables the user to retrieve the metadata. Currently, the metadata database in OLID houses 6000 metadata records that are accessible to the public, including records for 350 OGS publications.

The MNDM metadata records, through OLID, are also available for searches through GeoConnections (http://geodiscover.cgdi.ca [accessed October 6, 2005]), and the Geological Survey of Canada's Canadian Geoscience Knowledge Network (CKGN: http://cgkn.net/ [accessed October 6, 2005]).

SEDIMENTARY GEOSCIENCE SECTION PUBLICATIONS

Geoscientists of the Sedimentary Geoscience Section (SGS), pointed out that, with their current workloads, they did not have sufficient time to complete metadata records of their historical publications (some have upwards of 100 publications) within the requested time. In addition to their own publications, the "current" geoscientists were requested to complete records for publications co-authored with, and also authored by, "former" SGS–OGS geoscientists (i.e., those geoscientists formerly employed by OGS). Therefore, a new project was proposed to alleviate the backlog of metadata for SGS-related publications. The project lead (senior author Takats) was then assigned the task to set up a plan and begin the process of completing as many metadata records of SGS historical publications as possible. A preliminary search of the Publications Database for 34 former and 14 current SGS authors revealed an estimated 2285 publications that required metadata records.

PROJECT DESIGN AND IMPLEMENTATION

The objective of the SGS metadata project is to create metadata records for SGS historical publications published by OGS prior to December 2004. The SGS authors are still required to create the metadata for current work as it is released for publication.

Each "current" geoscientist was provided with a list of publications for which they were an author or co-author and assigned a unique author identification number (for internal purposes only). A similar list was created for "former" geoscientists (geoscientists who collaborated or worked at the OGS over the past ~25 years).

As discussed above, the LIO metadata entry tool software was installed onto each author's computer and includes a blank database containing an OGS-specific template. This template contains standard corporate and publication sales information, such as copyright, licencing agreement, and contact and distribution information. A standardized pick list of keywords and the mandatory business themes (Geology and Ontario Geological Survey) are in the application. However, some fields in the metadata directory entry tool are not suitable for OGS publications and are left blank.

The SGS metadata project was designed to generate the maximum number of metadata records daily with minimal errors and as efficiently as possible. Rather than creating metadata for publications by each author, one author at a time, and who may have published many different and unrelated works, it was more efficient to work on groups of publications with similar information. These publications are grouped by programs (e.g., Northern Ontario Engineering Terrain Studies (NOEGTS)), initiatives (e.g., Kirkland Lake Initiatives Program (KLIP)), or types of studies (e.g., Quaternary maps, Aggregate Resource Inventory Papers (ARIPs)), etc. The OGS-specific template was used as the base to generate program-specific templates, which were saved as individual "themed" Microsoft® Access databases. These templates were formulated to include information appropriate to all the similar publications in that group; for example, the description of the purpose and use of the publication, the list of keywords, and description of the data source are the same for each group of these program-specific publications. The fields containing information that change with each publication (e.g., title, author, year, etc.) are left blank or have a text "placeholder" in the template (*see* highlighted text in the example below). An additional aspect in template design is to maintain consistency in the descriptions of the publication series; it can also be used to create metadata records for future publications.

Each template, before its use in metadata record creation, was checked and verified for grammar, clarity and appropriate description of the publication series by staff of the Publication Services Section. The preparation of the templates took most of the time in the generation of the metadata. Collecting information for each template could take up to 1.5 to 2 weeks of research and writing.

The metadata entry tool user interface (*see* Figure 34.1) consists of sets of clearly labelled tabs located horizontally at the top of the application window and vertically along the right-hand side. The tabs related to general information and identification of the information holding are located vertically. The tabs are selected with the cursor. Each tab allows data entry via copy-and-paste commands, direct typing or selection from pick lists. The horizontal tabs group different types of information (*see* Figure 34.1). The program-specific templates contain as many completed fields as suitable in each of the tabs.

An example of a program-specific template (see example shown below) is that created for the Quaternary geology maps produced by SGS and published by OGS. Almost 300 Preliminary and Final maps, created by various authors, with varying publication dates, were found within the 2285 publications on the SGS list. The nature of the work, the information produced by the mapping, and the source data tend to be similar. In the example below, a portion of the template for Quaternary geology maps is shown with the option of a Preliminary (P####) or Final (M####) map.

Example

GENERAL INFORMATION

Official Name of the Data Set or Information Holding: 799 Copy "Title" from Excel Author's list: Quaternary Map Template

Acronyms are Used to Identify the Data Set or Information Holding: P#### or M####

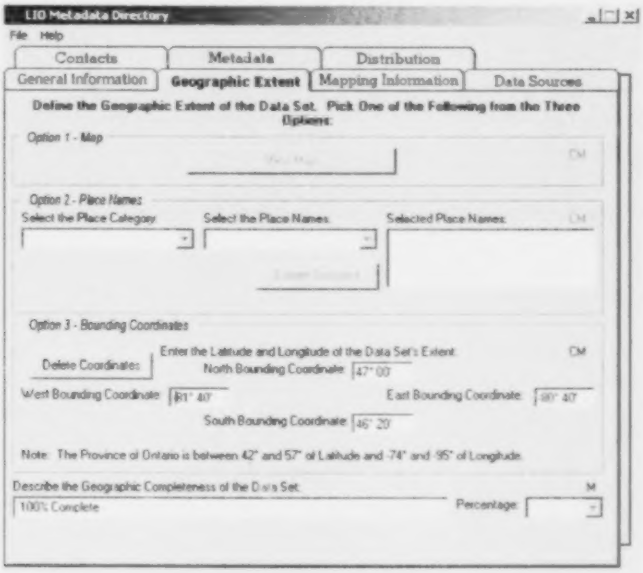
Describe the Data Set or Information Holding: Copy "Authors" as listed in Excel Author's list (authors)
A hard-copy colour uncoloured map of the Quaternary geology of the XXXX area, at the 1:50 000 scale, that covers 1:50 000 scale National Topographic System (NTS) map(s) XX X/##.
The map shows the distribution and characteristics of surficial units across the mapped area, including surficial deposit types, exposed bedrock, material types (till, etc.) and geological features (eskers, etc.).

The Intended Use and Purpose for Collecting the Data Set or Information Holding:
To provide a detailed overview of the surficial geology of the study area and associated attributes available to the land-use planning, consulting, mineral exploration industry, aggregate/industrial mineral industry and resource development community as well as government geoscientists, resource scientists, conservation authorities, land-use planners and academic researchers. The objective of this product is to collect and disseminate geoscience information for Ontario.

The highlighted text, in the example above, indicates that information specific to this publication is required. The numbers in front of the title are the internal author identification number, which is deleted after later review. In various parts of the template, a choice is given for map type, depending upon whether the publication is a Final or a Preliminary Map; for example, older preliminary maps are uncoloured, therefore, the word "colour" must be deleted from this record. Compare the template example above to the final metadata record for a Sudbury Quaternary map (*see* Figure 34.1).

The metadata entry tool application allows creation of only one record at a time; however, it is possible to copy from one record to another in the database. A full metadata record also can be copied, but certain key fields do not copy to the new record: specifically, the title and acronym, geographic extent, time field and one of the contacts for the publication distribution are not transferred. Several of these fields are "mandatory" without which the record cannot be saved to the MNDM metadata database. Therefore, the person doing the data entry must be aware of the missing fields in the copied record and the mandatory fields to complete the record. To aid completion of data entry, each template was exported from the metadata entry database as a document in hypertext mark-up language (*.html*) format, then copied into a Microsoft® Word document. This Word document remains open on the computer while generating new metadata records to visually verify the contents of fields and to re-insert information that may be inadvertently deleted.

For ease of generating metadata records, the Excel spreadsheet containing the basic publication information (title, author, date, etc.) also remained open on the computer to allow for direct copying of information. A program was created in Microsoft® Visual Basic® to input bounding coordinates (longitude and latitude) into the Geographic Extent tab (Figure 34.2, Option 3) for the publication's study area (including symmetrical, non-continguous or irregularly shaped areas). The selection and transfer of coordinates was easily accomplished by selecting townships or NTS grid sheets from a map-view window of Ontario and updating the metadata records. The program was easy to use and saved time in data entry. One of the quirks of the metadata entry tool application is that it does not allow geographic searching if only the place names are inserted into the metadata record (*see* Figure 34.2, Option 2). Thus, bounding coordinates (longitude, latitude) are required for all metadata records.



Define the Geographic Extent of the Data Set. Pick One of the Following from the Three Options:

Select the Place Category
Select the Place Names
Selected Place Names

Enter the Latitude and Longitude of the Data Set's Extent
North Bounding Coordinate: 47° 00'
West Bounding Coordinate: 81° 40'
East Bounding Coordinate: 80° 40'
South Bounding Coordinate: 46° 20'

Note: The Province of Ontario is between 42° and 57° of Latitude and -74° and -95° of Longitude.

Describe the Geographic Completeness of the Data Set: 100% Complete
Percentage:

Figure 34.2. LIO Metadata Directory entry tool user interface showing the Geographic Extent tab.

Quality control was carried out by selecting a set of metadata records from each themed database, exporting the records to HTML format and comparing a hard-copy print of the records to the original program-specific template and information from the actual publication. The final metadata records are saved in unique "themed" Microsoft® Access databases, and undergo editorial review before being uploaded to the MNDM metadata database and then into the OLID environment.

A contract employee (Eric Drouin) was trained on all aspects of the metadata project; in August, a second employee (Daniel Scholtz) received training on metadata record creation. As an example of the time frame during which a set of metadata records could be completed, for one series of publications (Northern Ontario Engineering Geology Terrain Study (NOEGTS)), Eric Drouin completed metadata records on 147 NOEGTS maps and 76 NOEGTS reports at an average rate of 12 per day. For approximately 4 months, there were 2 employees creating metadata templates and generating metadata records for publications. To date, more than 1250 metadata records have been generated.

REFERENCES

Government of Ontario. 1996. Geospatial Metadata Standard, Basic Content Requirements. GO-ITS 72.0; Management Board Secretariat, Information and Technology Standards Unit, Toronto, Ontario, 19p.

Romani, D. and Dumont, N. 2002. ERMES – Ontario's On-Line Geoscience Library; Ministry of Natural Resources, Land Information Ontario Program, LIO - Spatial News, May 2002, v.2, Issue 1, p.2-3, http://www.lio.mnr.gov.on.ca/spectrasites/internet/lio/media/documents/LIO-SpatialNews_Spring02.pdf [accessed October 6, 2005].

35. Project Unit 02-015. Regional Industrial Minerals and Diagenetic Study of the Guelph, Eramosa, and Amabel Formations, Southwestern Ontario

F.R. Brunton[1], **L.-K. Dekeyser**[2] **and M. Coniglio**[2]

[1]Sedimentary Geoscience Section, Ontario Geological Survey
[2]Department of Earth Sciences, University of Waterloo, Waterloo, ON N2L 3G1

INTRODUCTION

This industrial minerals and diagenetic study builds upon the regional-scale surface and subsurface stratigraphic studies of the Silurian-age Guelph, Eramosa and Amabel formations that have been carried out over the past century (e.g. Williams 1919; Shaw 1937; Bolton 1953, 1957; Liberty and Bolton 1971; Koepke and Sanford 1966; Sanford 1969; Sanford, Thompson and McFall 1985; Bailey 1986; Armstrong and Meadows 1988; Armstrong and Dubord 1992; Armstrong 1993a, 1993b) by providing insights into the many sedimentologic, stratigraphic and diagenetic features that are presently poorly understood. The study forms an integral part of the regional-scale industrial minerals inventory of these economically significant Silurian carbonates being carried out by the Ontario Geological Survey (OGS) (Brunton and Dekeyser 2004).

Despite more than 150 years of study, the relative ages, stratigraphic relationships, and depositional environments of these key industrial mineral-producing formations are still poorly constrained. In particular, the highly variable lithofacies that make up the Eramosa rock unit have been 1) given the rank of beds of the uppermost Lockport Formation by Williams (1919); 2) allocated formational rank by Shaw (1937) and Rickard (1975); 3) referred to as the upper member of the Lockport and Amabel formations by Liberty and Bolton (1971); and 4) assigned the basal member of the Guelph Formation by Sanford (1969) and geoscientists of the OGS (*see* Armstrong and Meadows 1988; Armstrong and Dubord 1992).

It is also important to note that both the Guelph Formation, which was introduced by Logan (1963), and the Eramosa lithofacies of Williams (1915a, 1915b, 1919) and as modified by Bolton (1953, 1957) and Liberty and Bolton (1971), have never been allocated type sections. This is one of the key requirements for the establishment of formational rank. The type section descriptions of the various members of the Amabel Formation are also contentious. Although rocks of this time interval and displaying similar sedimentological and paleontological character have been formally described from many jurisdictions throughout the Great Lakes region, the term Amabel Formation is used only in Ontario. It was introduced and a type section allocated by Bolton (1953, 1957), with modifications provided by Liberty and Bolton (1971). The Amabel Formation is restricted to Silurian dolostones that accumulated along the eastern margin of the Michigan Basin. It has been correlated with the Lockport Formation, which has its type section in northern New York State (Hall 1939; Zenger 1965). Rocks which span the Lockport interval, record the depositional and erosional events along the western margin of the Appalachian Basin, which extends into southern Ontario from Niagara Falls to the Hamilton–Waterdown area. Lockport lithofacies have been given both formational and group rank interchangeably over at least the past 45 years (Fisher 1960; Zenger 1965; Berry and Boucot 1970; Rickard 1975). This, too, is in violation of the North American Stratigraphic Code (NASC). A detailed discussion of the historical

---

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.35-1 to 35-7.

© Queen's Printer for Ontario, 2005

evolution of this complex rock nomenclature for these significant, cuesta-forming Silurian caprocks is beyond the scope of this paper (*see* Brett, Tepper, Goodman et al. 1995).

The regional scope of this industrial minerals and diagenetic study has demonstrated that Eramosa lithofacies should be given formational rank. Detailed field measurements have been made from more than 100 field stations, including stratigraphic sections from all key outcrops, operational and abandoned quarries, and more than 20 rock cores spanning all or most of these caprock formations along the entire Ontario portion of the Niagara Escarpment. This work verifies the regional continuity and lithologic variability, and temporal significance of this significant rock unit. Therefore, this paper will refer to those lithofacies assigned to the Eramosa interval by Williams (1915a, 1915b, 1919), Shaw (1937), Bolton (1953, 1957), Sanford (1969), Armstrong and Meadows (1988), Armstrong and Dubord (1992), and Smith (1990) as the Eramosa Formation. Although key lithologic characteristics for this rock unit are provided below, a detailed description and proper definition of the Eramosa Formation, including the provision of a type section for both the Eramosa and Guelph formations, will follow the publication of the OFR associated with this project. These descriptions will also be published in a formally recognized refereed journal to meet the requirements of the NASC.

INDUSTRIAL MINERALS INVENTORY AND DIAGENETIC STUDY

The purpose of industrial minerals inventories is to create a provincial geochemical database of key Paleozoic rock units and integrate the data within a regional stratigraphic and sedimentologic framework. Such integration of data benefits many groups: it enables the minerals industry to make informed exploration and exploitation decisions, it provides planners with necessary geologic information for inclusion in development projects, and provides rock chemistry data to be compared with groundwater and/or surface water chemistry data in and around the major urban centres of southern Ontario. At present, this multi-year industrial minerals assessment of the Guelph, Eramosa and Amabel dolostones comprises more than 100 field stations. This data will be integrated into a regional stratigraphic compilation of the key Silurian caprock units of the Niagara Escarpment. The expected completion of the Niagara Escarpment Guelph–Amabel formation diagenetic and industrial minerals and stratigraphic compilation is winter 2006–2007. The economic significance of these rocks has been summarized previously (Brunton and Dekeyser 2004).

The Guelph and Amabel formations provide ideal examples of dolomitized carbonates that are laden with complex macro and microfabrics, various types of stylolites and complex stylo-seam sets, vugs, and siliceous and gypsiferous nodules. These formations form the caprock of the Niagara Escarpment in Ontario and crop out extensively north of Owen Sound forming the spine and majestic vistas of the Bruce Peninsula. Selected drill cores were chosen throughout the Bruce Peninsula and City of Guelph regions in order to study regional variations and similarities of diagenetic fabrics along part of the eastern margin of the long-lived intracratonic Michigan Basin.

Eramosa dolostones and minor limestones and the underlying Wiarton/Colpoy Bay and Lions Head members of the Amabel Formation represent important dimension stone and aggregate quarry resources for both local industries and growing international markets. The diagenetic study will provide important information concerning the burial history of these carbonates and origins of various minerals phases, such as gypsiferous and chert nodules and pore-filling minerals. These mineral phases are detrimental for certain aggregate and chemical stone applications. To this end, a ground-penetrating radar (GPR) study was also carried out adjacent to 2 OGS drill holes and within 2 active buildingstone quarries on the Bruce Peninsula. This study was carried out to demonstrate how GPR may be used to delineate buildingstone resource potential of carbonates in and adjacent to quarries where drill-hole information is limited (Dekeyser et al. 2005). Other economic and exploration interest in these carbonates stems from their ability to be both a hydrocarbon source rock and reservoir, and as a possible Mississippi Valley-type lead-zinc deposit. The Niagaran reefs within these formations have accommodated more than 150 oil and gas pools in the subsurface of southwestern Ontario (Carter, Trevail and Smith 1994; Coniglio, Zheng and Carter 2003).

GEOLOGIC SIGNIFICANCE

The Guelph Formation comprises open marine medium- to thickly bedded cross-stratified crinoidal grainstones and wackestones and lagoonal thinly bedded megalodont-gastropod-dominated wackestones and packstones, and lesser biostromal and biohermal reefal complexes. These lithofacies conformably overlie and/or are lateral to bituminous, argillaceous, less fossiliferous dolostones of the generally underlying Eramosa Formation. The Eramosa Formation is more laterally continuous along the Niagara Escarpment than is generally depicted in the literature. It is a very significant rock unit because it is both a petroleum source rock and reservoir, and the host of sulphide mineralization in the form of sphalerite, galena, and pyrite. Sphalerite appears to be the key mineral phase north of the Algonquin Arch (a northeast-trending basement structure located in vicinity of Guelph), and galena appears to be more prevalent south of the arch.

The Eramosa Formation is a most intriguing rock unit because, where exposed as bedrock, it may display significant response to karstification due to its uniform crystallinity (e.g., Eramosa Karst, Stoney Creek; Buck, Worthington and Ford 2003), but, where buried beneath Guelph Formation lithofacies and underlain by Amabel Formation crinoidal grainstones or bryozoan-microbial reef mounds, the more restricted lagoonal mud-rich and microbial mat-bearing Eramosa lithofacies may act as an aquitard, separating overlying unconfined bedrock aquifers of the Guelph Formation from confined aquifers of the underlying Amabel Formation. In general, the Eramosa dolostone has been interpreted as a restricted marine lagoonal carbonate unit. More recent field work reveals that the Eramosa dolostone displays significant regional variability in fossil content and sedimentary structures depicting abrupt temporal and spatial changes in depositional environments between the Michigan and Appalachian basins.

This rock unit possesses a wide range of biologically and sedimentologically produced fabrics, including subtidal thrombolitic to laminar stromatolitic microbial mats displaying no evidence of subaerial exposure; to biostromal and small biohermal complexes possessing a low diversity bryozoan-microbial-coral composition to stromatoporoid-tabulate coral-bryozoan-microbial composition; to finely to medium crystalline, variably nodular and stylo-seamed wackestones and mudstones displaying evidence of variable horizontal bioturbation and storm deposition. Fabrics include a possible seismite bed at Wiarton and at the Williams (1919) Guelph Line railway cut. Some rock outcrops in the Guelph area display evidence of more open marine storm-influenced deposition, including features such as swaley cross-stratification (SCS) or possibly hummocky cross-stratification (HCS).

The underlying Amabel Formation is generally composed of blue-gray medium- to thickly bedded dolomitized crinoidal grainstones displaying highly variable porosity and permeability. These grainstones form regionally extensive submarine dune complexes. Other regionally significant lithofacies comprise thinly to medium-bedded heavily stylo-seamed, vuggy and pseudo-nodular wackestones and packstones. Small-scale patch reef complexes are present, but not as abundant as purported in the literature. They occur sporadically throughout the outcrop–subcrop belt and comprise a mixture of bryozoan-microbial-dominated cementstone fabrics with fewer tabulate corals and stromatoporoids and commonly associated benthic-nektic faunas such as crinoids, brachiopods, trilobites, gastropods and nautiloids. Lithofacies within this formation generally record more transitional temporal and spatial variations in fossil content and sedimentary fabrics than the overlying Guelph Formation. These temporal variations reflect changes in marine conditions from more restricted marine to open marine conditions along the eastern margin of the Michigan Basin and western extremities of the Appalachian basin where the so-called Lockport–Amabel facies transition occurs.

These economically significant rock units are in need of reinterpretation with the aid of regional mapping, borehole correlation and ground-penetrating radar. Utilization of excellent rock core spanning this Silurian time interval has enabled for both a better understanding of the regional lithofacies and geochemical variability and local and regional controls on the composition, porosity and economically-significant rock properties of the Amabel, Eramosa and Guelph formations.

ASSOCIATED THESIS WORK

The main objective of the MSc thesis project by L.-K. Dekeyser is to outline the diagenetic properties of the Amabel, Eramosa and Guelph dolostones. A second objective is to show that GPR can be used to characterize these formations in thin-drift and exposed bedrock areas where subsurface data are absent to assess the nature of bedding in relation to such features as karst-related dissolution and/or resource potential of building stone quarries. This project will clarify key stratigraphic and petrographic details of these strategically important dolostone bedrock units in southern Ontario, and will add useful geochemical data regarding their role as bedrock aquifers and sources of aggregate and building stone.

The diagenetic study comprises 2 components: 1) a petrologic and geochemical study of carbonate fabrics within the Guelph–Amabel formations found within 8 OGS drill cores extending from Tobermory to Allenford on the Bruce Peninsula and 3 additional cores from Guelph; and 2) a GPR study of these Silurian bedrock units adjacent to 2 of the OGS boreholes on the Bruce Peninsula and to shallow boreholes and quarry faces at the Owen Sound Ledgerock Wiarton Quarry and Adair Quarry near Lions Head on the Bruce Peninsula (Figure 34.1). Sampling and field descriptions of the 11 cores selected for the diagenetic study were conducted in June and July, 2005. Samples were chosen based on fabrics, member contacts, pore cements, vugs, and nodule content to decipher the diagenetic history of the rocks and help explain why particular lithofacies are subject to dissolution and/or silicification. A total of 190 samples were taken from these 11 boreholes, and 167 of these samples were cut into pucks and thin sectioned in order to study the petrographic nature of the dolomites. Petrographic and geochemical studies will be carried out through fall and winter of 2005–2006 and completion of an Open File Report is expected in fall 2006.

Ground-penetrating radar (GPR) surveys were completed near 2 OGS borehole locations, as well as at the Owen Sound Ledgerock Wiarton Quarry and Adair Quarry near Lions Head. These surveys aim to provide clarity to the geophysical relationship between the radar signal and the physical properties of each of the formations. Preliminary results of the high-resolution and deeper-penetrating lower resolution surveys were presented at the annual GAC–MAC conference in Halifax (Dekeyser et al. 2005).

The dolostones of the Guelph and Amabel formations possess high chemical purity levels, making them one of the most desirable resources in the province for the industrial minerals industry (Brunton and Dekeyser 2004). Their geographic position with regard to both the formation and location of the Niagara Escarpment has resulted in these strata playing a significant role as a key bedrock aquifer in southern Ontario and growing ecotourism destination. Given the continued population growth and demands on an aging industrial infrastructure within the key urban centres on and adjacent to the Niagara Escarpment in southern Ontario, the economic (aggregate, building stone, chemical stone), recreational and strategic (groundwater aquifer) importance of these rock units requires new studies using a modern understanding of lithofacies analysis and carbonate diagenesis in conjunction with geophysics.

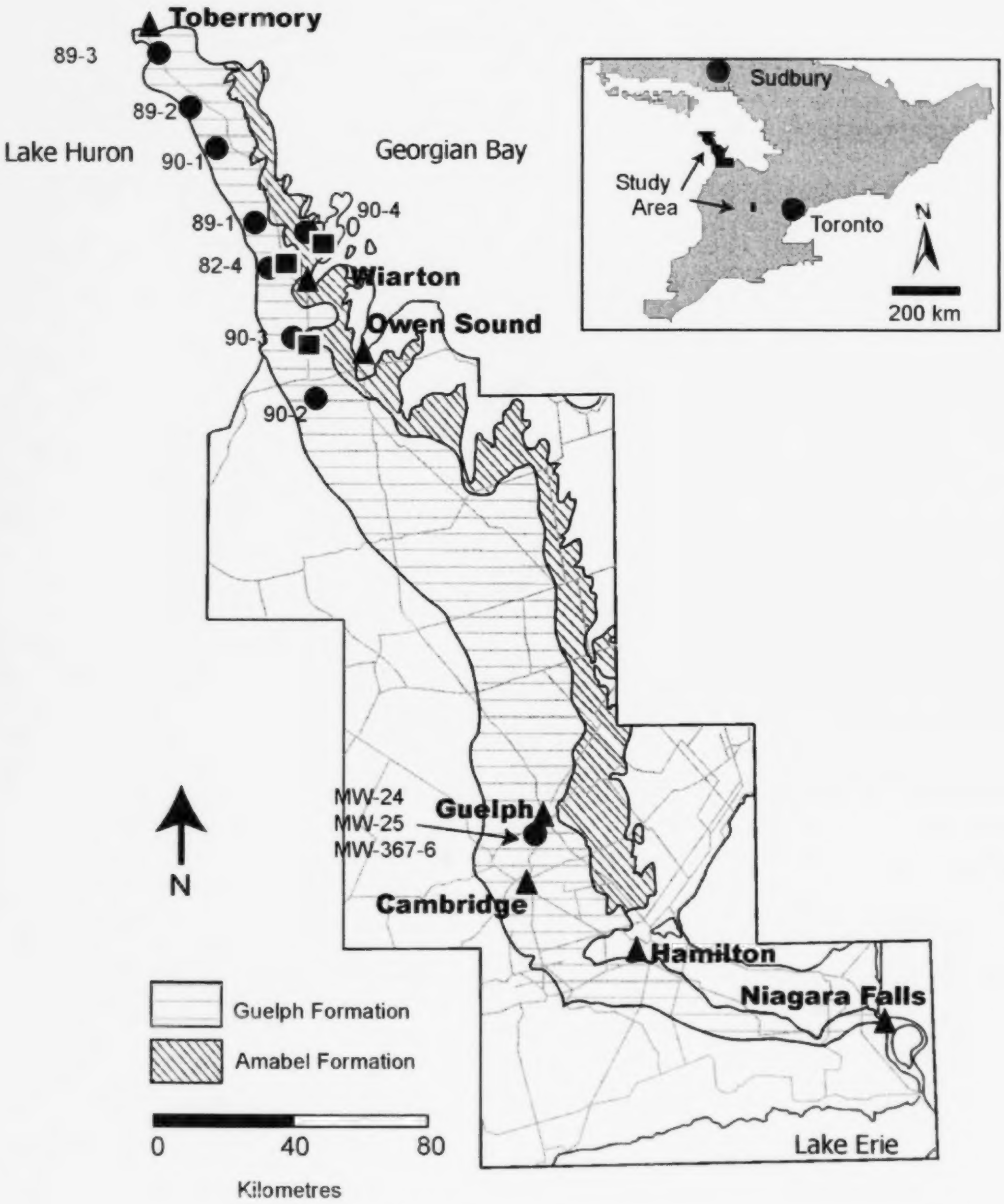

Tobermory
89-3
89-2
Lake Huron
90-1
Georgian Bay
89-1
90-4
82-4
Wiarton
Owen Sound
90-3
90-2
Sudbury
Study Area
Toronto
N
200 km
MW-24
MW-25
MW-367-6
Guelph
Cambridge
N
Hamilton
Niagara Falls
Guelph Formation
Amabel Formation
0
40
80
Kilometres
Lake Erie

Figure 34.1. Outcrop and subcrop distributions of Niagara Escarpment caprock lithofacies spanning the Guelph–Amabel time interval, southern Ontario. Triangles denote locations of various cities and towns along escarpment: the dots show locations of OGS (Bruce Peninsula) and Guelph borehole locations, and the boxes show locations of ground-penetrating radar (GPR) field sites. The inset map of southern Ontario shows regional extent of diagenetic study for L.-K. D. These dolostones represent the primary bedrock found on the Bruce Peninsula and the caprock units of the Niagara Escarpment in Ontario. Caprock units south of Hamilton and extending to Niagara Falls have been referred to as both the Lockport Group and/or Lockport Formation.

ACKNOWLEDGEMENTS

Dr. Beth Parker (University of Waterloo; Gamsby and Mannerow Ltd.) kindly provided access and sampling of the Guelph drill core to L.-K.D. and F.R.B. Dekeyser's research is supported by the Ontario Geological Survey and Natural Science and Engineering Research Council of Canada Discovery grants awarded to Coniglio. Dave Belanger, City of Guelph Public Works, kindly provided access to rock core collected as part of the various groundwater studies carried out over past five years. Support and access to the Oil, Gas, and Salt Resource drill core library administered by the Ontario Petroleum Institute (OPI), London, Ontario is also acknowledged, in particular Richard Ostrowski (OPI), and Terry Carter (Ministry of Natural Resources).

REFERENCES

Armstrong, D.K. 1993a. Paleozoic geology of the central Bruce Peninsula; Ontario Geological Survey, Open File Report 5856, 19p.

——— 1993b. Paleozoic geology of southern Bruce Peninsula, southern Ontario; Ontario Geological Survey, Open File Report 5875, 19p.

Armstrong, D.K. and Dubord, M.P. 1992. Paleozoic geology, northern Bruce Peninsula, southern Ontario: Ontario Geological Survey, Open File Map 198, scale 1:50 000.

Armstrong, D.K. and Meadows, J.R. 1988. Stratigraphy and resource potential of the Eramosa member (Amabel Formation), Bruce Peninsula, Ontario; Ontario Geological Survey, Open File Report 5662, 89p.

Bailey, S.M.B. 1986. A new look at the development, configuration and trapping mechanisms of the Silurian Guelph reefs of southwestern Ontario; Ontario Petroleum Institute, 25th Annual Conference, Technical Paper 14, 28p.

Berry, W.B.N. and Boucot, A.J. 1970. Correlation of the North American Silurian rocks; Geological Society of America, Special Paper 102, 289p.

Bolton, T.E. 1953. Silurian formations of the Niagara Escarpment in Ontario; Geological Survey of Canada, Paper 53-23, 19p.

——— 1957. Silurian stratigraphy and paleontology of the Niagara Escarpment in Ontario; Geological Survey of Canada, Memoir 289, 145p.

Brett, C.E., Tepper, D.H., Goodman, W.M., LoDuca, S.T. and Eckert, B.Y. 1995. Revised stratigraphy and correlations of the Niagaran provincial series (Medina, Clinton, and Lockport Groups) in the type area of western New York; United States Geological Survey, Bulletin 2086, 66p.

Brunton, F.R. and DeKeyser, L.-K. 2004. Industrial mineral potential of the Guelph Formation and the Eramosa Member of the Amabel Formation, southwestern Ontario; *in* Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.19-1 to 19-5.

Buck, M.J., Worthington, S.R.H. and Ford, D.C. 2003. Earth Science Inventory and evaluation of the Eramosa Karst area of natural and scientific interest; Ontario Ministry of Natural Resources, Guelph District, southcentral region, 51p.

Carter, T.R., Trevail, R.A. and Smith, L. 1994. Core workshop: Niagaran reef and inter-reef relationships in the subsurface of southwestern Ontario; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Waterloo 1994, Field Trip A5, Guidebook, 38p.

Coniglio, M., Zheng, Q. and Carter, T.R. 2003. Dolomitization and recrystallization of middle Silurian reefs and platformal carbonates of the Guelph Formation, Michigan Basin, southwestern Ontario; Bulletin of Canadian Petroleum Geology, v.51, p.177-199.

Dekeyser, L., Endres, A.L., Coniglio, M., Armstrong, D.K., Brunton, F.R. and Tetreault, D. 2005. Resolution of shallow subsurface stratigraphy in Silurian dolostones, Bruce Peninsula, southern Ontario: insights from ground-penetrating radar; Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists–Canadian Society of Soil Science, Joint Annual Meeting, Halifax, Program with Abstracts, v.30, p.43.

Fisher, D.W. 1960. Correlation of the Silurian rocks in New York State; New York State Museum and Science Service, map and chart series no. 1.

Hall, J. 1939. Third annual report of the Third Geological District of New York; New York Geological Survey, Annual Report 3, p.287-339.

Koepke, W.E. and Sanford, B.V. 1966. The Silurian oil and gas fields of southern Ontario; Geological Survey of Canada, Paper 65-30, 137p.

Liberty, B.A. and Bolton, T.E. 1971. Paleozoic geology of the Bruce Peninsula area, Ontario; Geological Survey of Canada, Memoir 360, 163p.

Logan, W.E. 1863. Geology of Canada; Geological Survey of Canada, Progress Report to 1863, p.336.

Rickard, L.V. 1975. Correlation of Silurian and Devonian rocks in New York State; New York State Museum and Science Service Map and Chart Series No. 24, 4 plates, 16p.

Sanford, B.V. 1969. Silurian of southwestern Ontario; Ontario Petroleum Institute, 8th Annual Conference Proceedings, Technical Paper No. 5, p.1-44.

Sanford, B.V., Thompson, F.J. and McFall, G.H. 1985. Plate tectonics—A possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario; Bulletin of Canadian Petroleum Geology, v.33, p.52-71.

Shaw, E.W. 1937. The Guelph and Eramosa formations of the Ontario peninsula; Transactions of the Royal Canadian Institute, v.21(2), no.46, p.317-362.

Smith, L. 1990. Geologic controls on porosity and permeability variation in Silurian pinnacle reef bioherms, southwestern Ontario; Ontario Petroleum Institute Inc., Twenty-Ninth Annual Conference, Technical Session No. 2, Paper No. 4, London, Ontario, p.1-19.

Williams, M.Y. 1915a. The Middle and Upper Silurian of southwestern Ontario; Geological Survey of Canada, Summary Report 1914, p.82-86.

——— 1915b. An eurypterid horizon in the Niagara Formation of Ontario; Geological Survey of Canada, Museum Bulletin No. 20, 21p.

——— 1919. The Silurian geology and faunas of Ontario Peninsula, and Manitoulin and adjacent islands; Geological Survey of Canada, Memoir 111, 195p.

Zenger, D.H. 1965. Stratigraphy of the Lockport Formation (Middle Silurian) in New York State; New York State Museum and Science Service, Bulletin No. 404, 210p.

Geoscience Laboratories

36. Sample Preparation: Sample Size Considerations

J. Schweyer[1] and E. Stairs[1]

[1]Geoscience Laboratories, Ministry of Northern Development and Mines, 933 Ramsey Lake Road, Sudbury, Ontario

---

INTRODUCTION

Sample preparation refers to the process of air-drying, crushing, splitting, grinding, pulverizing, sieving, and homogenizing a gross sample for the purpose of obtaining a representative subsample of the entire original sample (Merks 1985; Johnson and Maxwell 1981). Contamination during the sample preparation procedure will always be present. Ingamells and Pitard (1986, p.75) have stated, "It is, of course, impossible to collect, reduce, grind, screen, and mix rock or mineral samples without introducing some contamination from the equipment and the environment". With that in mind, the goal during sample preparation is one of minimizing critical contaminants. Since there is no way to avoid contamination during the sample preparation procedure, it is important to fully understand the composition of the materials used to make the crushing and grinding equipment. By knowing the composition of the crushing and grinding equipment, and the specific requirements of the clients, appropriate crushing and grinding media can be selected to minimize these critical contaminants.

The Geoscience Laboratories (Geo Labs) has developed a routine set of standard operating procedures in sample preparation that minimize contamination. The procedure involves sorting the samples, crushing the samples using a jaw crusher, riffling to split the sample into a representative subsample (approximately 150 g), grinding the split, sieving the pulp to ensure that 95% is less than –170 mesh, homogenenizing the pulp after grinding, and transferring the pulp to a labelled bottle for analysis. Most of the samples received at the Geo Labs are in excess of 200 g. Occasionally, samples with less than 150 g are submitted for analysis. This has recently lead to an issue at the Geo Labs involving the impact of samples submitted for analysis that are considerably less than 150 g and how the composition of the submitted samples can be changed when the routine set of standard operating procedures are applied. An experiment was designed to test the impact of varying sample weights using the current set of standard operating procedures in sample preparation.

EXPERIMENT

The experiment was designed to evaluate the potential level of contamination from the planetary mills using the current standard operating procedures. There were six different sample weights (30, 60, 90, 120, 150 and 180 g), two different types of grinding media (Al_2O_3 and agate), and two different instrument set-up speeds (320 and 360 rpm) used in the experiment. The agate mills were only run at a speed of 320 rpm, whereas the Al_2O_3 mills were run at 320 and 360 rpm. The length of time for pulverizing the samples was kept consistent with the current standard operating procedure at 40 minutes in order to monitor the potential impact on previously prepared samples. The different combinations of sample size, grinding media, and instrument set-up speed were run in triplicate. The material used in this study was a Lorrain Formation quartzite that is routinely used to clean the jaw crushers and planetary mills between samples. The quartzite was chosen due to its hardness, which should represent one of the worst-case scenarios. The pulverized samples were fused into glass discs that were analyzed for Al_2O_3 using wavelength dispersive X-ray fluorescence (XRF) on a Rigaku RIX-3000.

Summary of Field Work and Other Activities 2005,
Ontario Geological Survey, Open File Report 6172, p.36-1 to 36-2.

© Queen's Printer for Ontario, 2005

RESULTS

It is accepted that one of the main sources of contamination during sample preparation will be from the grinding media itself. Therefore, the results presented will only be for the major constituent of the planetary mills routinely used at the Geo Labs. The Al_2O_3 or alumina mills are most frequently used at Geo Labs due to their robustness and cost effectiveness. The XRF results for Al_2O_3 are represented in Figure 36.1. It should be noted that during the experiment one of the Al_2O_3 planetary mills broke using a 30 g sample at a speed of 360 rpm. The agate mills were used in this study to provide a baseline for comparative purposes. The agate mills are not used for routine sample preparation due to their higher purchase cost, the potential for SiO_2 contamination and reduced robustness. The Geo Labs does have a limited set of agate mills available for use.

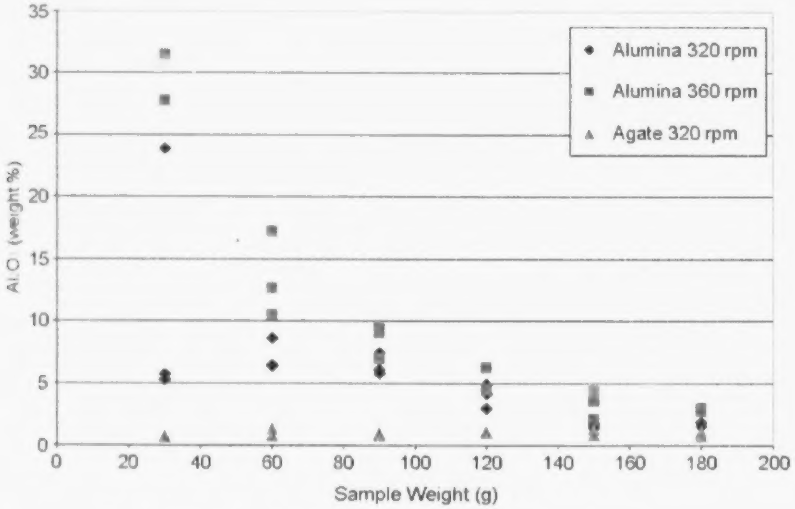


Figure 36.1. Plot of Al_2O_3 concentrations as a function of sample size.

SUMMARY AND IMPLICATIONS

When using the Al_2O_3 mills and the current standard operating procedures, it is evident that the potential for Al_2O_3 contamination does exist for samples that are less than 150 g. Changes have been instituted in the sample preparation procedures to help minimize this. Reduction of instrument set-up speeds to 320 rpm and increased training to recognize the potential contamination risks while preparing small sample masses have been implemented. When handling samples that are less than 150 g, alternative methods are being used. The use of agate mills is being utilized as well as reducing the length of time during pulverizing using the Al_2O_3 mills.

REFERENCES

Ingamells, C.O. and Pitard, F.F. 1986. Applied geochemical analysis; John Wiley and Sons, Toronto, 733p.

Johnson, W.M. and Maxwell, J.A. 1981. Rock and mineral analysis, second ed.; John Wiley and Sons, Toronto, 489p.

Merks, J.W. 1985. Sampling and weighing of bulk solids; Trans Tech Publications Inc., Clausthal-Zellerfeld, Germany, 410p.

Index of Authors (with corresponding article numbers)

A

Abbey, D., 31
Armstrong, D.K., 29
Ayer, J.A., 4, 8

B

Bajc, A.F., 25
Baker, C.L., 2
Barnett, P.J., 20
Beakhouse, G.P., 9
Berger, B.R., 5, 6, 7
Boyd, J.W., 34
Brunton, F.R., 22, 27, 28, 31, 35
Burt, A.K., 26

C

Calhoun, R., 4
Clark, I.D., 19
Coniglio, M., 35

D

Davies, S.D., 30
Dekeyser, L.-K., 35
Dodge, J.E.P., 27, 29
Drouin, E.G., 34
Dyer, R.D., 23, 24

E

Easton, M.G., 34
Easton, R.M., 13, 14, 15

F

Felix, V.E., 21
Fyon, J.A., 1, 2

G

Gale, D., 32
Gao, C., 22

H

Hamilton, M.A., 8
Hamilton, S.M., 19, 23
Hart, T.R., 12, 14
Hattori, K.H., 19
Holysh, S., 30
Houlé, M.G., 7
Hurley, J., 31

K

Kamo, S.L., 15
Kelly, R.I., 28, 29

M

Madon, Z.B., 17, 18
Merry, A.G., 31, 33
Muir, T.L., 16

N

Newsome, J., 2
Newton, M.J., 25
Nicks, L.P., 33

P

Parker, J.R., 2, 3
Préfontaine, S., 5, 6, 7

R

Rainsford, D.R.B., 16
Rayner, N., 10
Russell, D.F., 26

S

Sarvas, P., 32
Scholtz, D.J., 34
Schweyer, J., 36
Shirota, J., 22, 27, 28
Stairs, E., 36
Stone, D., 11
Stott, G.M. 10

T

Takats, P.A., 34
Trowell, N.F., 17

V

Vaillancourt, C., 8
van Haaften, S., 22

W

Wadley, S., 31

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

ISSN 0826-9580 (print)
ISBN 0-7794-9135-1 (print)
ISBN 0-7794-9136-X (PDF)